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TECHNICAL MANUAL

No. 5-858-6

HEADQUARTERS
DEPARTMENT OF THE ARMY
Washington, DC, *31 August 1984*

DESIGNING FACILITIES TO RESIST NUCLEAR WEAPONS EFFECT HARDNESS VERIFICATION

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CHAPTER 1
INTRODUCTION

1-1. General.

a. This series of manuals, entitled Designing Facilities to Resist Nuclear Weapon Effects, is organized as follows:

TM 5-858-1 Facilities System Engineering
TM 5-858-2 Weapon Effects
TM 5-858-3 Structures
TM 5-858-4 Shock Isolation Systems
TM 5-858-5 Air Entrainment, Fasteners, Penetration Protection, Hydraulic-Surge Protective Devices, EMP Protective Devices
TM 5-858-6 Hardness Verification
TM 5-858-7 Facility Support Systems
TM 5-858-8 Illustrative Examples

A list of references pertinent to each manual is placed in an appendix. Additional appendixes and bibliographies are used, as required, for documentation of supporting information. Pertinent bibliographic material is identified in the text with the author's name placed in parentheses. Such bibliographic material is not necessary for the use of this manual; the name and source of publications related to the subject of this manual is provided for information purposes.

b. The purpose of this series of manuals is to provide guidance to engineers engaged in designing facilities that are required to resist nuclear weapon effects. It has been written for systems, structural, mechanical, electical, and test engineers possessing state-of-the-art expertise in their respective disciplines, but having little knowledge of nuclear weapon effects on facilities. While it is applicable as general design guidelines to all Corps of Engineers specialists who participate in designing permanent military facilities, it has been written and organized on the assumption a systems-engineering group will coordinate design of the facilities.

c. Technical Manual 5-858 addresses only the designing of hardened facilities; other techniques to achieve survival capacity against nuclear weapon attacks are deception, duplication, dispersion, nomadization, reconstitution, and active defense. A facility is said to be hardened if it has been designed to directly resist and mitigate the weapon effects. Most of the hardening requirements are allocated to the subsidiary facilities, which house, support, and protect the prime mission materiel/personnel (PMMP). This manual is applicable to permanent facilities, such as those associated with weapon systems, materiel stockpiles, command centers, manufacturing centers, and communications centers.

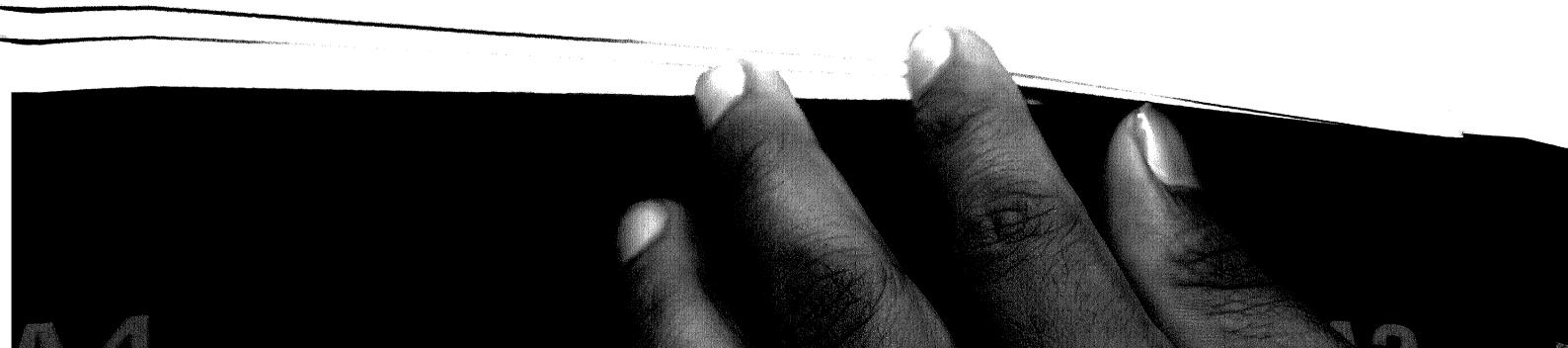
d. The nuclear weapon threats considered are listed below. Biological, chemical, and conventional weapon attacks are not considered.

—Weapons aimed at the facility itself or at nearby targets
—A range from many, relatively small-yield weapons to a single super-yield weapon
—Weapon yields from tens of kilotons to hundreds of megatons
—Weapon delivery by aerial bombing, air-to-surface missile, surface-to-surface missile, or sattelite-launched vehicle
—Detonation (burst) of a weapon in the air, at the ground surface, or beneath the ground surface
—Direct-overhead bursts for a deep-buried facility
—Near-miss bursts for a near-surface facility, producing peak over-pressures from tens to thousands of psi at the facility

e. The designing of facilities resistant to nuclear weapon effects is an evolving speciality using a relatively narrow data base that incorporates both random and systematic uncertainities. The range of these uncertainties may vary from significant (order of 1 to 2 magnitudes) to normal (10 to 100 percent variation from average values). The applicable uncertainity value depends on the specific weapon effect or hardening objective under consideration. Loading uncertainity is generally more significant than resistance uncertainty. Awareness of the appropriate uncertainty (extent of ignorance) factor is essential not only for system engineering trade-offs, but in the utilization of available analysis or test procedures. Studies and experiments are being conducted to improve methodology, to better define random uncertainties, and to reduce systematic uncertainties. This manual will be revised as significant improvements occur in either methodology or data base.

1-2. TM 5-858-6: Hardness verification.

This volume presents methodology for verifying the hardness of the facilities. The methodology comprises both physical and mathematical simulations. A synopsis of available testing facilities is given.



CHAPTER 2
GENERAL METHODOLOGY

2-1. Introduction.

a. A hardness verification program for protective facilities and their systems, subsystems, and elements measures the ability to survive an attack that has been specified in terms of weapon size, range, and burst conditions and of particular site characteristics. When nuclear test ban treaties precluded atmospheric nuclear testing, alternative testing techniques and analytical procedures were developed to assess the probability of a facility surviving a prescribed attack. Most protective facilities are extremely complex, containing major systems that require methodical testing at the subsystem level and integration of the results; this analytical methodology is called hardness verification.

b. Hardness verification must be made at regular intervals during the facility development/design/construction cycle. Simple verifications will be performed during the initial design phases. As designs become firm and fabrication begins, more comprehensive verifications will be made. It is essential that hardness verification be used periodically to monitor the iterative process of definition, systhesis, design (redesign), analysis, test, and evaluation that transforms mission requirements to demonstrable and acceptable facility survivability. This will secure continuing integrity between design and construction, will verify that each element, subsystem, and system has been combined in a manner that properly accounts for uncertainties in responses and the interdependence of various physical parts of the facility.

c. The analyst must know the failure modes and resistances for the relevant elements of the subsystem or higher level assemblages, and the local weapon-effect loads on those points. Whether from experimental tests or from analyses, the data provided must include uncertainties associated with each mean value. This volume deals primarily with procedures to evaluate failure modes and resistances; techniques to deal with the random nature of the process are discussed in chapters 5 and 6.

2-2. Identification and organization of system elements.

a. The first task in system hardness verification is to define the physical system. The relationship of each element to mission critical functions must be accurately defined and the associated local loads and failure modes must be specified. For complete examination of a facility, network logic analysis including the use of Boolean algebra is strongly recommended. The construction of fault trees within the context of multilevel system organization is a procedure will suited to the solution of complex problems dealing with verification activities.

b. The fault-tree approach provides for the analysis of all elements, subsystems, and systems, and includes every factor that influences the hardness (or failure) of each element and consequently each subsystem and system. It graphically represents the logic that relates the failure mode(s) of system elements to a particular weapon effect(s). That is, the fault tree organizes failure-mode/weapon-effect combinations into a logic network, thereby allowing use of probabilistic information in descriping the hardness of each element, subsystem, and system.

c. The multilevel system organization views the protective facility as a hierarchy of systems, subsystems, and elements:

—Level 1: Complete Faciltiy
—Level 2: Complete Sytems
—Level 3: Subsystems within Complete Systems
—Level 4: Elements within Subsystems

(1) System Level 1 represents the finished facility, complete with protective and protected systems.

(2) System 2 includes complete functional systems that make up a particular facility. Included in this category are both the protective and the protected systems. There are generally nine protective systems:

—Structure
—Shock isolation
—Air entrainment
—Anchors, mounts, and fasteners
—Penetration
—Hydraulic-surge protective devices
—EMP protective devices
—Radiation shielding
—Thermal shielding and fire barrier

The protected systems include:

—Power supply
—Power distribution
—Cooling
—Heating and ventilation
—Water supply
—Sewage disposal
—Lighting
—Communication
—Prime-mission materiel
—Personnel

If required by the facility mission, other protected systems may also exist in the facility.

(3) System Level 3 includes the complete functional subsystems that make up a system. For example, the various subsystems of the air-entrainment system are:

—Intake structure
—Expansion chamber
—Blast attenautor
—Blast valve
—Delay line
—Filtration

(4) System Level 4 includes the components of the various subsystems. For example, the blast valve subsystem of the air-entrainment system would have components such as:

—Valve hardware elements
—Attachment hardware parts
—Actuation components
—Sensor elements

d. Typical hardened facilities will include thousands of structure and equipment items. It is impractical and unnecessary to verify the hardness of each item. The analyst must define some consistent method for the selection (or screening) of items. The specifics of the method may differ from system to system, but a fairly universal approach includes these four basic steps:

(1) Identify those items of equipment that are critical mission success. (Note: the noncritical items must not pose a threat to the critical items when damaged or destroyed during attack.)
(2) Identify those critical items that are susceptible to the weapon effect.
(3) Identify those items that have marginal hardness. Omit items having a large factor of safety. List items that obviously will fail and must be redesigned.
(4) From each population of different items remaining, randomly select a statistically significant sample for test or perform probabilistic computations to verify hardness.

2-3 Weapon-effect loads.

a. After the items have been selected for verification, identify local loads induced by one or more of the free-field nuclear weapon-effect environments. Identify the total signal path and path segments leading from the free field to the ele ment. Determine the transfer function for eac path segment. In some instances, the inputs to b used for hardness verification will be the same a those used for design purposes; in other instance the inputs will be determined by extensive testin and analytic programs.

b. Identifying the total transmission path is bes performed by applying network logic analysi (chap. 6).

c. Determining transfer functions is the proces of relating free-field nuclear environments to local loads in order to assess hardness levels. Transfer functions may be determined experimentally; more often, an analytical procedure will be employed.

2-4. Quantifying resistances.

a. The resistance of a system, subsystem, or element is defined as its ability to withstand nuclear weapon-effect loads. The load-resisting characteristics may be quantified by experimental data (laboratory or field) or by analysis of mathematical models. Scarcity of experimental data may require augmentation from computational models to accrue a statistically significant body of data.

b. Data from either laboratory or field tests are preferred for determining resistance. Tests can be conducted on prototypes or scale models; but in order to be statistically meaningful, a significant number of tests must be conducted. (See chap 3 for the statistical implications of testing; see chap 4 for the types of tests available.) If testing is not possible because of technical difficulties or lack of equipment, time, or funds, a computational analysis will be required.

c. Analytical procedures, especially numeric techniques, are the backbone of many of the verification studies applied to hardened systems. Although deterministic analytical procedures have reached an advanced state of development, probabilistic analyses that allow for the computation of uncertainties and survival problbilities are markedly less familiar. Thus, the performance of verification analyses according to the guidelines in chapter 6 will require considerable ingenuity. Some guidelines to the development of probabilistic procedures that can be applied to real systems are presented in chapter 5.

CHAPTER 3
STATISTICAL PROCEDURES

1. Introduction.

. Statistical techniques are usually associated h laboratory testing. Application of these techues to field testing, and especially to the statisl inferences of calculations, is still in an early te of development; consequently, the verificaiton lyst will not have the benefit of extensive preis work.

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3-2. Probabilistic distribution.

a. Ask the following questions: Is it necessary to define a specific type of distribution? If so, what type of distribution should be selected?

b. For many (if not all) of the analyses to be conducted, the definition of the exact distribution will not critically affect the results. (See Aitchison-Brown, 1969; Benjamin-Cornell, 1970.) This is true for the following circumstances:

—If the distribution is not grossly nonlinear near the mean

—If the uncertainty parameter $\Omega = \frac{\sigma}{\mu}$ is small (i.e., $\Omega^2 << 1.0$)

where

σ = The true standard deviation

μ = The true mean

These assumptions are equivalent to ignoring the tails of the distribution (i.e., at those responses exceeding, say, $\pm 3\sigma$). These assumptions will almost always be acceptable for verification analyses. Furthermore, the normal or log normal distribution will provide an adequate approximation in most cases. Whether the normal or log normal model is adopted because of physical considerations or as an approximation to another distribution, it will be sufficiently accurate in practical applications.

c. If a normal distribution cannot be adopted, then either conduct enough tests (usually >30) that the assumption of a particular distribution can be defined (using, for instance, a chi square goodness-of-fit test), or transform the data so that the normal assumption may be made, or use a distribution-free analysis. Others may be used, but only if these are not suitable.

d. The normal, or t statistic, distribution is the single most-used model in applied probability analyses (Benjamin-Cornell, 1970). The normal distribution asymptotically represents the sum of a number of random events. For example, it represents how a manufactured or constructed item deviates from a specified performance value because of flaws or errors in the many separate components of the item. Therefore, the normal distribution is a prime candidate to represent the random

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c. Hardness verification generally is not conducted to answer Question (1) because it is much more costly to determine what the resistance is than it is to determine whether the resistance is above or below some specified level. If undertaken, the result will be a mean resistance with a corresponding variance or uncertainty for each weapon-effect failure-mode combination. By combining the resistance for all t modes of failure, the mean-resistance/uncertainty for a particular system or subsystem will be determined.

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deviations of resistance from a specified level, since this resistance nearly always results from a sum of contributing components.

e. Adopt the normal distribution whenever assumptions in b above can be accepted. Use it also whenever adequate tests are available and the assumption of normality is confirmed through a chi-square (χ^2) test. (The performance of the chi-square test is described in most of the references in statistics included in this volume.)

f. If the variables are known to result from the multiplication of many effects (still assuming *b* above), use the lognormal distribution instead of the normal. However, when $\Omega^2 << 1$, there will be no significant difference between the normal and lognormal results. In this volume only the normal (t) distribution is discussed; a complete discussion of the lognormal distribution is presented by Aitchison-Brown (1969).

g. Select the nonparametric distribution instead of the normal when assumptions in b cannot be accepted and another particular distribution cannot be confirmed.

h. Select the binomial distribution only when "fail or succeed" information is acquired through tests at a specified level.

3-3. Analysis for resistance.

a. Experiments can be designed to determine the resistance of a single weapon-effect/failure-mode combination for a simple element, or of combined resistance for a total system or complex subsystem. In either case, conduct enough independent trials or tests to statistically determine the resistance(s) of interest, usually >30 samples.

b. In experimental verification it will not be possible to "exactly" identify the resistance of interest. The best that can be done is to bracket the resistance. Ideally, bracketing is done by starting the testing at a level where design analysis has shown there will be a high probability of success, and then increasing the level in small increments until failure occurs. The resistance then lies between the level where failure occurred and the level just before failure. Obviously, the smaller the incremental change in load level, the more accurately the resistance can be bracketed for the item. Generally, specify the resistance as the last level where success occurred. If, however, large increments (greater than ¼ of the resistance) must be used because of costs, a higher level might be taken. But never specify a level more than one-half of the increment above the last level of success; and support such a resistance level by rigorous analysis.

c. Because testing total systems is expensive, the resistance of a total hardened system must usually be determined by combining the results of many element or subsystem tests. The resistance of an element, subsystem, or system is always related to one or more weapon-effect/ failure-mode combination(s). It is critically important to adequately simulate the weapon effect of interest and accurately measure the resulting repsonses.

d. The use of statistics in testing for resistance is different than statistics used in calculating resistance. For experimental verification, a number of tests are performed on the system, subsystem, or element to define its statistical performance. In calculated verification, the mathematical model for the system, subsystem, or element is deterministic but its constitutive parpameters such as stiffness, weight, and strength are allowed to have a statistical character so that for each selection of parameters chosen a unique response will be obtained. The calculations that result will have much the same character as test data that result from experimental verification.

3-4. Mean and variance by normal, t, distribution.

a. Given a sample of n data (such as resistance measurements), the sample mean value and variance are defined as

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3\text{-}1)$$

$$s^2 = \frac{1}{n}\sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad (3\text{-}2)$$

or

$$\hat{s}^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad (3\text{-}3)$$

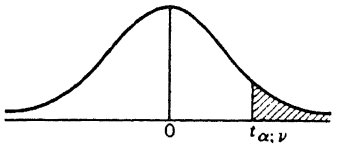
where

n = Number of samples
$s^2, \hat{s}^2$ = Sample variances
$\bar{x}$ = Sample mean
x_i = Individual sample values

Equation 3-3 is presented as a better estimate of the variance for $n \leq 30$.

Table 3-1. Percentage Points of the t Distribution

(Table of $t_{\alpha;\nu}$ — the 100 α percentage point of the t distribution for ν degrees of freedom [$\nu = n - 1$])



ν \ α	.40	.30	.20	.10	.050	.025	.010	.005	.001	.0005
1	.325	.727	1.376	3.078	6.314	12.71	31.82	63.66	318.3	636.6
2	.289	.617	1.061	1.886	2.920	4.303	6.965	9.925	22.33	31.60
3	.277	.584	.978	1.638	2.353	3.182	4.541	5.841	10.22	12.94
4	.271	.569	.941	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	.267	.559	.920	1.476	2.015	2.571	3.365	4.032	5.893	6.859
6	.265	.553	.906	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	.263	.549	.896	1.415	1.895	2.365	2.998	3.499	4.785	5.405
8	.262	.546	.889	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	.261	.543	.883	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	.260	.542	.879	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	.260	.540	.876	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	.259	.539	.873	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	.259	.538	.870	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	.258	.537	.868	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	.258	.536	.866	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	.258	.535	.865	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	.257	.534	.863	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	.257	.534	.862	1.330	1.734	2.101	2.552	2.878	3.611	3.922
19	.257	.533	.861	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	.257	.533	.860	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	.257	.532	.859	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	.256	.532	.858	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	.256	.532	.858	1.319	1.714	2.069	2.500	2.807	3.485	3.767
24	.256	.531	.857	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	.256	.531	.856	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	.256	.531	.856	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	.256	.531	.855	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	.256	.530	.855	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	.256	.530	.854	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	.256	.530	.854	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	.255	.529	.851	1.303	1.684	2.021	2.423	2.704	3.307	3.551
50	.255	.528	.849	1.298	1.676	2.009	2.403	2.678	3.262	3.495
60	.254	.527	.848	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	.254	.527	.846	1.292	1.664	1.990	2.374	2.639	3.195	3.415
100	.254	.526	.845	1.290	1.660	1.984	2.365	2.626	3.174	3.389
200	.254	.525	.843	1.286	1.653	1.972	2.345	2.601	3.131	3.339
500	.253	.525	.842	1.283	1.648	1.965	2.334	2.586	3.106	3.310
∞	.253	.524	.842	1.282	1.645	1.960	2.326	2.576	3.090	3.291

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b. The optimum procedure for testing the hypothesis that the mean of a normal distribution has some specified value $\mu = \mu_0$) is based on the t test statistic, where:

$$t = \frac{x - \mu_0}{\hat{s}}\sqrt{n-1} = \frac{x - \mu_0}{\hat{s}}\sqrt{n} \qquad (3\text{-}4)$$

c. The acceptance region for a two-sided procedure (where the hypothesis is stated as = $_0$) is

$$-t\alpha/2,n-1 < t < t\alpha/2,n-1 \qquad 3\text{-}5$$

where t is calculated from equation 3-4 with $\mu = \mu_0$ and α is the level of significance for the test; i.e. there is a probability of $1-\alpha$ of accepting the hypothesis $\mu = \mu_0$ when it is true. The values of $t_{\alpha/2,n-1}$ are taken from tables of t statistics such as table 3-1. By combining equations 3-4 and 3-5,

$$\bar{x} - t_{\alpha/2,\, n-1}\frac{\hat{s}}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2,n-1}\frac{\hat{s}}{\sqrt{n}}$$

The values $\bar{x} \pm t_{/2,n-1'}\frac{\hat{s}}{\sqrt{n}}$ are the confidence limits and bound the confidence interval. Equation 3-6 states that μ lies within the given confidence interval. This statement will be true 1 - α fraction of the time.

d. In many instances the analysis to determine the resistance will require answering this question: Is the resistance equal to or greater than a specific value? This allows use of the one-sided procedure based on the hypothesis: $\mu = \mu_0$. In this case, the acceptance region is

$$t \geq -t_{,n-1}$$

The hypothesis is accepted if equation 3-7 is satisfied, but is rejected otherwise. This procedure also has the probability of 1 - α of accepting the hypothesis when it is true.

e. As stated above, 1 - α is the confidence level or the probability of accepting the hypothesis when it is true. Conversely, the probability of rejecting the hypothesis when it is true is given by α. This is called a Type I error. The value of a is selected by the analyst, using input from the systems manager. For resistance verification analysis, α should range between 0.05 and 0.10. The smaller the value of α, the larger the confidence interval. In the extreme case it would be possible to have a probability of 0.9999 $(1 - \alpha)$ that the true mean falls in an interval so large as to be meaningless. This is particularly true for small n.

f. A second probability is called the Type II error, which is denoted by β. The analyst selects β to represent the probability of accepting the hypothesis when it is considered important to detect the value of the ratio $(\mu_1 - \mu_0/\sigma$, where σ=true standard deviation of the population and is unknown. In other words, β is the probability of accepting the hypothesis H_0: $\mu = \mu_0$ when actually $\mu = \mu_1$. The analyst must choose values of μ_1 and σ such that the ratio $(\mu_1 - \mu_0)$ is meaningful to the analysis.

g. Once β and the ratio $\mu_1 = \mu_0/\sigma$ have been selected, operating characteristics curves such as those shown in figures 3-1 and 3-2 can be used to determine n. This procedure is illustrated by the following example, for which three problems and solutions are presented.

Example:

Item	Air-entrainment port closure
Weapon Effect	Airblast
Failure Mode	Stress
Resistance Design Goal	Pressure wave: Rise time (t_r) =0.002 sec Max. pressure (P_m) =1000 psi ($_0$ =1000 psi, e.g.) Decay time (t_d) =0.100 sec (time to decay to $P_m/2$)

Problem 1: The closure was designed to resist 1000 psi. Can the design be considered successful at a level of significance of, say, $\alpha = 0.05$? Four resistance values have been determined.

Calculate $\bar{x}$ (mean value of sample)
$\hat{x}$ (variance of sample)
C.I. (confidence interval)

Test Data $x_1 = 900$ psi
$x_2 = 1100$ psi
$x_3 = 950$ psi
$x_4 = 1000$ psi

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} = x_i \frac{900+1100+950+1000}{4}$$

(using equation 3-1)

$= 987.5$ psi

$$\hat{s}^2 = \frac{1}{n-1}\sum_{i=1}^{n} (\bar{x}_i - \bar{x})^2 \text{ (using eq. 3-3)}$$

$$= \frac{1}{3}\{(900-987.5)^2 + (1100-987.5)^2 + (950-987.5)^2$$

$\hat{s} = 85.4$ psi

$$t = \frac{x-\mu}{\hat{s}}\sqrt{n} = \frac{987.5-1000}{85.4} \times 2 = -0.29$$

(using eq. 3-4)

$\alpha/2 = 0.05/2 = 0.025$

$n-1 = 3$

From table 3-1, $t_{0.025,\,3} = 3.182$

Since $-3.182 < -0.29 < 3.182$, the hypothesis that $\mu = 1000$ is accepted at $\alpha = 0.05$

C.I. $= 987.5 - 3.182 \times \frac{85.4}{2}$ to $987.5 + 182 \times \frac{85.4}{2} = 852$ to 1123 psi.

Therefore, it can be stated that the mean resistance of the population lies between 852 psi and 1123 psi, with a confidence of of 95 percent that the statement is true. (Had $\alpha = 0.10$ been selected for the analysis, then it could be stated that the mean resistance of the population lies between 887 psi and 1088 psi, with a confidence of 90 percent that the statement is true; and for $\alpha = 0.20$, the C.I. = 918 to 1057 psi.)

Problem 2: Can the mean resistance be considered equial to or greater than 1000 psi with $\alpha = 0.05$?

One-Sided Procedure:

The acceptance region is $t \geq -t_{a,n-1}$

From the example:

$t = -0.29$

$\alpha = 0.05$

$n-1 = 3$

From table 3-1: $t_{0.05,3} = 2.353$

Since -0.29 >2.353, the hypothesis is accepted at a level of $\alpha = 0.05$.

$$\text{C.I.} = x - t_{\alpha,n-1}\frac{\hat{s}}{\sqrt{n}} \quad \text{to}$$

Or it can be considered that the C.I. has a lower limit only:

$$x - t_{a,n-1}\frac{s}{\sqrt{n}} = 987.5 - 2.353 \times \frac{85.4}{2} \quad (3\text{-}6)$$

$= 887$ psi

It can be stated that the mean resistance of the population is equal to or greater than 88 psi, with a confidence of 95 percent.

Problem 3: What is the value of β for the above sample of n =4?

Two-Sided Procedure:

Let $d = \frac{\mu_1 - \mu_0}{\sigma} = 2.0$ (from f above)
If it is assumed that $\hat{s}$ is a reasonable estimate of σ, then

$\sigma = 85.4$ psi.

Since $\mu_0 = 1000$ psi, then $\mu_1 = 2$ X 85.4 +1000 =1171 psi.
β gives the probability of accepting the hypothesis that $\mu = 1000$ when actually $\mu = 1171$ (or 829). β is found by using figure 3-1. The intersection of the n =4 curve and the d =2 value shows that β would be approximately 0.244. Therefore, for the sample tested there is a probability of 0.244 of accepting $\mu = 1000$ psi, when actually is could be as low as 829 psi or as high as 1171 psi.

One-Sided Procedure:

Let $d = \frac{\mu_0 - \mu_1}{\sigma} = 2.0$

Again, $\sigma = 85.4$ psi

$\mu_1 = 829$ psi

β is found by using figure 3-2. β is seen to be equal to approximately 0.25. Therefore, for the sample tested there is a probability of 0.25 of accepting $\mu \geq 1000$, when actually it could be as low as 829 psi.

3-5. Nonparametric distributions.

a. Distribution-free methods are utilized when the conditions specified in paragraph 3-2*b* do not apply or if the data set does not readily fit any other recognizable distribution.

b. Use of nonparametric methods requires the same kinds of tests as the t statistic described above. These tests would result in a measurement o the resistance level. The nonparametric results assert that a particular proportion (p) of the population has failure thresholds falling within a certain range. The statement has an associated confidence level (P). Procedures for calculation of the mean and variance are not defined.

c. Using this method, it can be stated with the probability (P) of being correct that no less than a particular proportion (p) of the population has failure thresholds between the maximum and minimum value of the failure levels observed in a sample of n tests. As before, the probability (P) is the level of confidence. The range between the maximum and minimum is analogous to the confidence interval.*

d. Assuming that the distribution is continuous and that x denotes the proportion of the population values that falls within the maximum and minimum values of any random sample of size n, the distribution of x (see Fisz, 1963) is given by

$$f(x) = n(n-1)x^{n-2}(1-x) \qquad (3\text{-}8)$$

Then

$$p = 1 - {}_{np}{}^{n-1} + (N-1)p^n$$

An approximation for n from equation 3-8 is

$$n \simeq 0.24\, \chi^2_{\alpha,4} \frac{1+p}{1-p} + 0.5 \qquad (3\text{-}9)$$

where

p = The proportion of the population that will fall within the sample range

$\chi^2_{\alpha,4}$ = The chi-square distribution for 4 degrees of freedom

$1-\alpha$ = The confidence level (α is the level of significance)

Equation 3-9 is plotted in figure 3-3 for selected values of $P = 1 - \alpha$.

*The interval between any two observations may be used as a confidence interval, but here only the sample range is discussed. of Sample Size

e. Analyses can also be performed based on the distribution of exceedances. Some significant inferences can be made from limited sample sizes. Harris (1952) develops the equation

$$P = 1-(1-p)^n$$

where P is the probability that in a future very large sample, the proportion p or less of the observations will fall below the minimum value * observed in a trial sample of size n. (It is also the proportion that will exceed the maximum value observed in the sample.) Equation 3-10 is plotted in figure 3-4 for selected values of n.

*For the r^{th} smallest value, $P = \sum_{s=r}^{n} p^s(1-p)^{n-s}(s)\ n.$

Example:

Data:

$n = 6$
$x_1 = 850$ psi
$x_3 = 900$ psi
$x_5 = 1050$ psi
$x_{min} = 850$ psi
$x_{max} = 1100$ psi
$x_2 = 1100$ psi
$x_4 = 1000$ psi
$x_6 = 950$ psi

Problem: What proportion of the population can be expected to have resistance levels in the range from 850 to 1100 psi with a confidence level of 80 percent?

The solution can be calculated from equation 3-9 with

$n = 6$
$\alpha = 0.2$
$\chi^2_{\alpha\,4} = 5.989$ (from table 3-2)

or can be found from the curves of figure 3-3. From either approach it is found that p = 57 per-

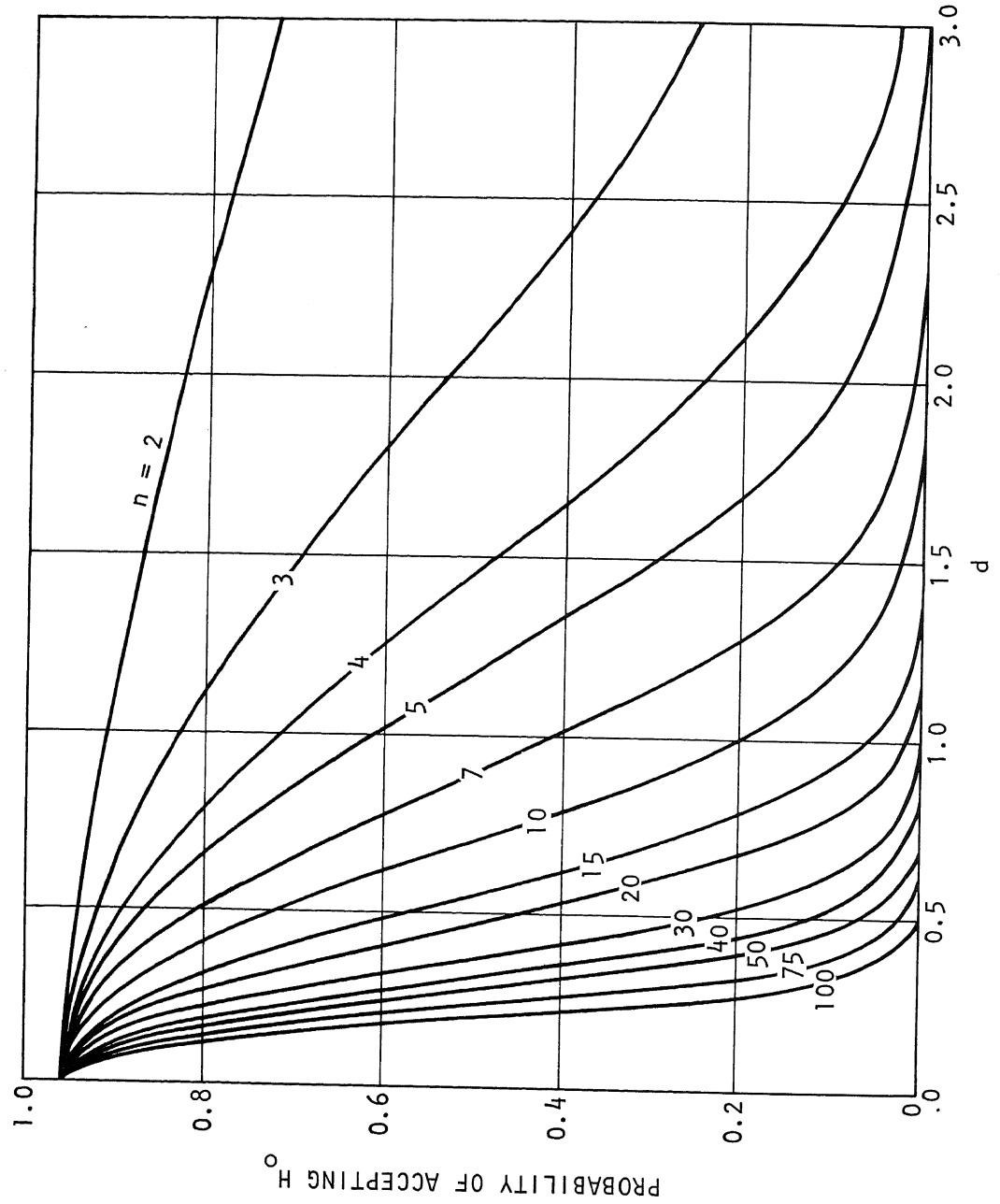
TABLE 3-2. THE χ^2 DISTRIBUTION (Adapted from Bowker-Lieberman, 1959)

α	0.99	0.98	0.95	0.90	0.80	0.70	0.50	0.30	0.20	0.10	0.05	0.02	0.01
d.f. = 1	0.0^3157	0.0^3628	0.0^2393	0.0158	0.0642	0.148	0.455	1.074	1.642	2.706	3.841	5.412	6.635
2	0.0201	0.0404	0.103	0.211	0.446	0.713	1.386	2.408	3.219	4.605	5.991	7.824	9.210
3	0.115	0.185	0.352	0.584	1.005	1.424	2.366	3.665	4.642	6.251	7.815	9.837	11.345
4	0.297	0.429	0.711	1.064	1.649	2.195	3.357	4.878	5.989	7.779	9.488	11.668	13.277
5	0.554	0.752	1.145	1.160	2.343	3.000	4.351	6.064	7.289	9.236	11.070	13.388	15.086
6	0.872	1.134	1.635	2.204	3.070	3.828	5.348	7.231	8.558	10.645	12.592	15.033	16.812
7	1.239	1.564	2.167	2.833	3.822	4.671	6.346	8.383	9.803	12.017	14.067	16.622	18.475
8	1.646	2.032	2.733	3.490	4.594	5.527	7.344	9.524	11.030	13.362	15.507	18.168	20.090
9	2.088	2.532	3.325	4.168	5.380	6.393	8.343	10.656	12.242	14.684	16.919	19.679	21.666
10	2.358	3.059	3.940	4.865	6.179	7.267	9.342	11.781	13.442	15.987	18.307	21.161	23.209
11	3.053	3.609	4.575	5.578	6.989	8.148	10.341	12.899	14.631	17.275	19.675	22.618	24.725
12	3.571	4.178	5.226	6.304	7.807	9.034	11.340	14.011	15.821	18.549	21.026	24.054	26.217
13	4.107	4.765	5.892	7.042	8.634	9.926	12.340	15.119	16.985	19.812	22.362	25.472	27.688
14	4.660	5.368	6.571	7.790	9.467	10.821	13.339	16.222	18.151	21.064	23.685	26.873	29.141
15	5.229	5.985	7.261	8.547	10.307	11.721	14.339	17.322	19.311	22.307	24.996	28.259	30.578
16	5.812	6.614	7.962	9.312	11.152	12.624	15.338	18.418	20.465	23.542	26.296	29.633	32.000
17	6.408	7.255	8.672	10.085	12.002	13.531	16.338	19.511	21.615	24.769	27.587	30.995	33.409
18	7.015	7.906	9.390	10.865	12.857	14.440	17.338	20.601	22.760	25.989	28.869	32.346	34.805
19	7.633	8.567	10.117	11.651	13.716	15.352	18.338	21.689	23.900	27.204	30.144	33.687	36.191
20	8.260	9.237	10.851	12.443	14.578	16.266	19.337	22.775	25.038	28.412	31.410	35.020	37.566
21	8.897	9.915	11.591	13.240	15.445	17.182	20.337	23.858	26.171	29.615	32.671	36.343	38.932
22	9.542	10.600	12.338	14.041	16.314	18.101	21.337	24.939	27.301	30.813	33.924	37.659	40.289
23	10.196	11.293	13.091	14.848	17.187	19.021	22.337	26.018	28.429	32.007	35.172	38.968	41.638
24	10.856	11.992	13.848	15.659	18.062	19.943	23.337	27.096	29.553	33.196	36.415	40.270	42.980
25	11.524	12.697	14.611	16.473	18.940	20.867	24.337	28.172	30.675	34.382	37.652	41.566	44.314
26	12.198	13.409	15.379	17.292	19.820	21.792	25.336	29.246	31.795	35.563	38.885	42.856	45.642
27	12.879	14.125	16.151	18.114	20.703	22.719	26.336	30.319	32.912	36.741	40.113	44.140	46.963
28	13.565	14.847	16.928	18.939	21.588	23.647	27.336	31.391	34.027	37.916	41.337	45.419	48.278
29	14.256	15.574	17.708	19.768	22.475	24.577	28.336	32.461	35.139	39.087	42.557	46.693	49.588
30	14.953	16.306	18.493	20.599	23.364	25.508	29.336	33.530	36.250	40.256	43.773	47.962	50.892

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Figure 3-2. Operating Characteristics Curves for Different Values of n

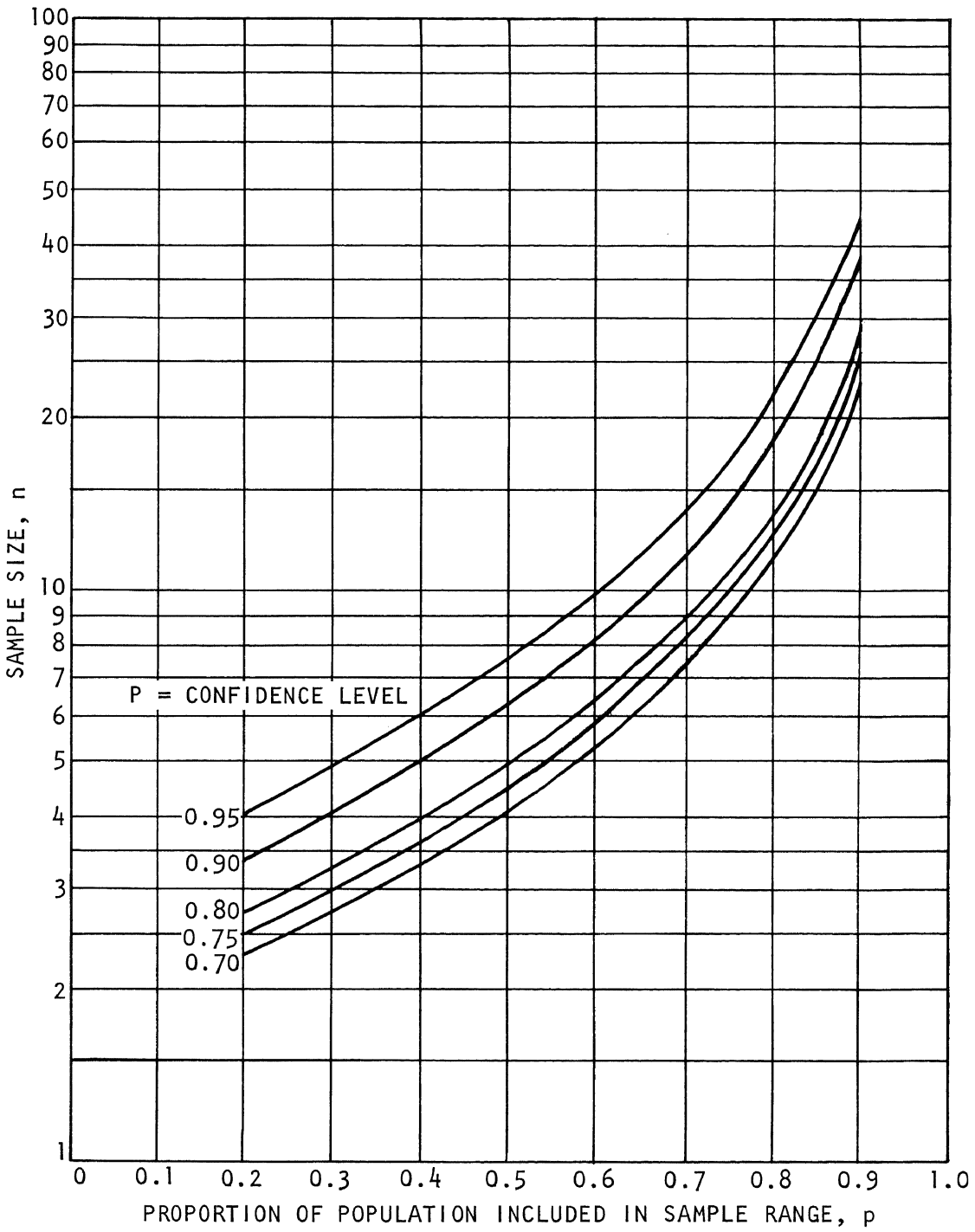
Figure 3-1. Operating Characteristics Curves for Different Values of n



(Albert H. Bowker, Gerald J. Lieberman, ENGINEERING STATISTICS, ©1959, pp. 41, 132, 190. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.)

FIGURE 3-1. OPERATING CHARACTERISTICS CURVES FOR DIFFERENT VALUES OF n FOR THE TWO-SIDED t TEST FOR A LEVEL OF SIGNIFICANCE $\alpha = 0.05$

Figure 3-3. Percentage of Population Within Sample Range as a Function



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FIGURE 3-3. PERCENTAGE OF POPULATION WITHIN SAMPLE RANGE AS A FUNCTION OF SAMPLE SIZE

cent. Thus, it can be asserted with a confidence of 80 percent that 57 percent at least of the population will have resistances falling in the range from 850 psi to 1100 psi. No inferences can be made for the remaining 43 percent. (Harris, 1952)

f. Inferences using distribution of exceedances can be made using the same data presented above.

Problem: With a confidence of 80 percent, what is the maximum proportion of a future very large sample which could be expected to fall below the 850-psi minimum of the sample of 6 observations?

The answer can be calculated from equation 3-10 above by solving for p with n =6

P =0.80

Or the curves in figure 3-4 can be used. From either approach,

p ~ 23.5percent

Thus, no more than 23.5 percent of a large sample from the population can be expected to have resistances below 850 psi with a confidence of 80 percent.

3-6. Binomial distribution.

a. As stated previously (para. 3-1), the verification of whether the resistance of a system is equal to or greater than a specified hardness level requires a somewhat different approach than determining the level of the resistance. This approach uses the statistical inferences of a binomial distribution.

b. The data that will be used in the analysis will be "failure-success" type of information: Did the system, subsystem, or element fail or succeed under test or in the calculation when subjected to the specified environment? When performing verification testing this does not eliminate the need to fully instrument the test item to acquire all pertinent response data. Comprehensive instrumentation becomes more important as the specimen and test costs increase.

c. Verification tests or analyses for this type of investigation are conducted at a specified hardness level, usually the design hardness goal. However, tests or calculations can also be conducted at levels exceeding the hardness goal. Such a decision is made by the verification analyst in conjunction with the designer and system manager. If tests or calculations are to be performed at levels other than the design goal, the level must be related to the design goal through analysis that is performed separately from the verification analysis presented in this volume (i.e., a full quantal response analysis).

d. Acquisition of resistance data and the analysis for determining whether the resistance is at least the specified hardness level will follow basically the same sequence of steps as for the resistance level itself (para. 3-4). The hardness compliance data will almost always be composed of fewer than 30 samples. However, as previously stated, the statistical inferences will be made from a binomial distribution because of the "go/no-go" or "pass-fail" nature of the data. The basic information required for the verification analysis is provided below.

e. The confidence intervals can be determined for two conditions:

$$P(s=r \mid n,p) = \frac{n!}{r!(n-r)!} p^r q^{n-r} \qquad (3\text{-}11)$$

which gives the probability of realizing exactly s=r successes in n trails (where the probability of success for any one trial is p, [q =1− p]; p can take any value from 0 to 1; 0<p<1. Alternatively,

$$P(s \geq r \mid n,p) = \sum_{s=r}^{n} \frac{n!}{s!(n-s)!} p^s q^{n-s} \qquad (3\text{-}12)$$

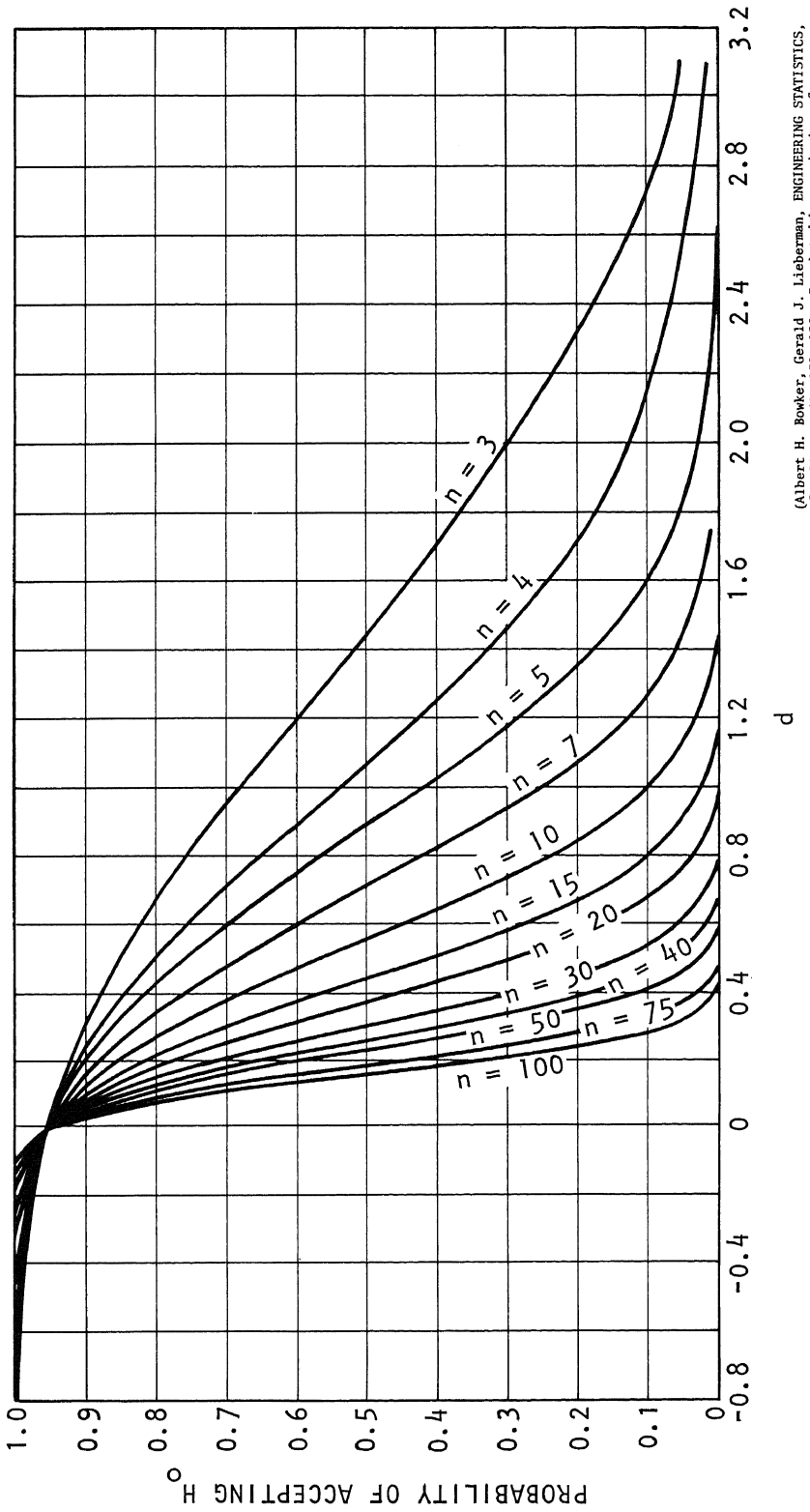
which gives the probability of realizing r or more (s≥r) successes in n trials.

f. Both equations 3-11 and 3-12 can be evaluated directly or tables may be used. Extensive tables are included in Abramowitz-Stegun (1972), and for values up to n =10 are included for convenience in appendix A.

g. Generally, equation 3-12 will be used in the verification analysis, since the question usually posed to the verification analyst is: "Is the resistance equal to or greater than $\bar{r}$, where $\bar{r}$ =r/n?", rather than, "Is the resistance exactly equal to $\bar{r}$?"

h. In the population being considered (the total number of like elements, subsystems, or systems in the total deployed system), an unknown proportion

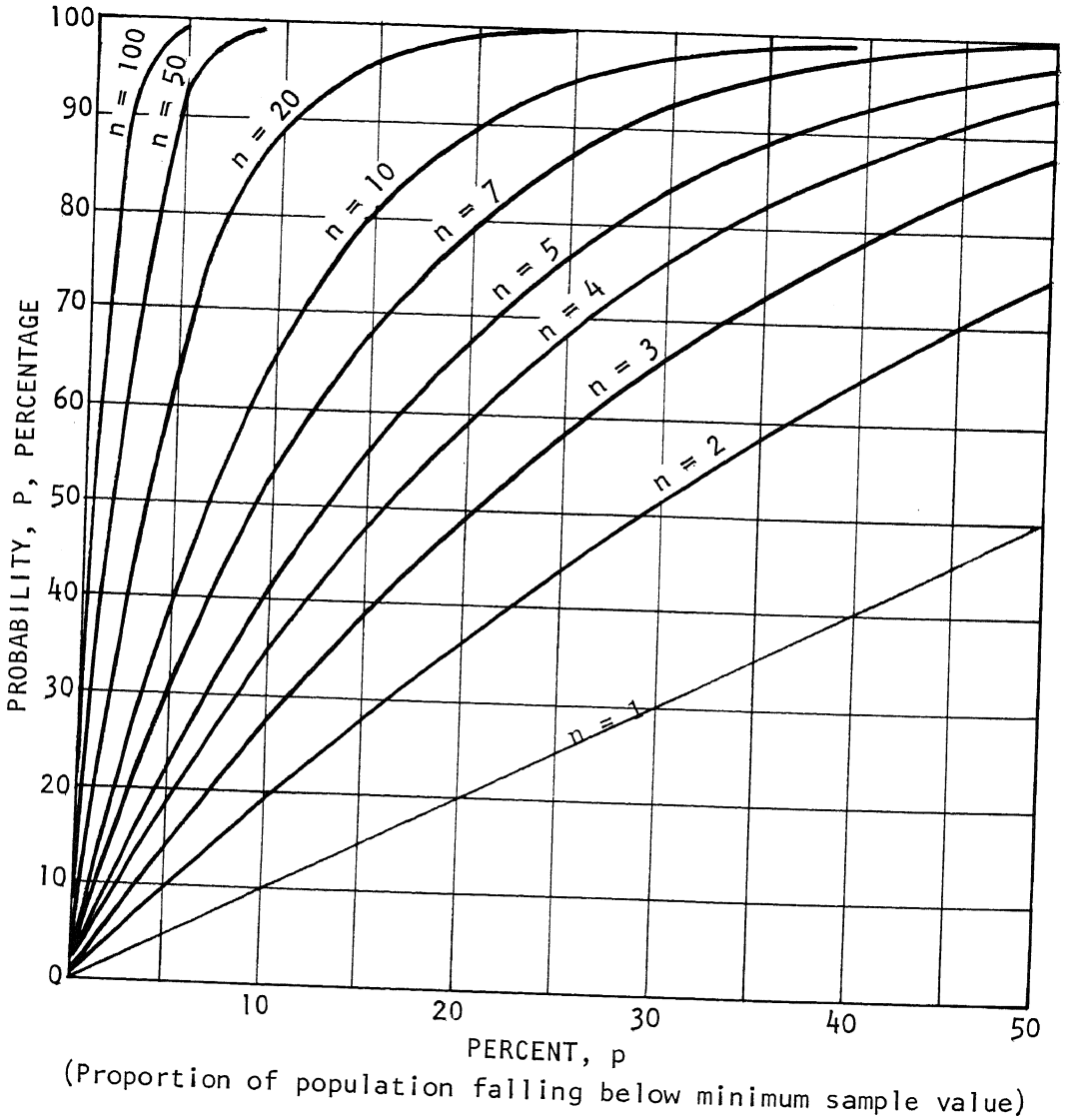
Table 3-2. The x^2 Distribution



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FIGURE 3-2. OPERATING CHARACTERISTICS CURVES FOR DIFFERENT VALUES OF n FOR THE ONE-SIDED t TEST FOR A LEVEL OF SIGNIFICANCE $\alpha = 0.05$

Figure 3-4. Percentage as a Function of Sample Size and Probability



of items will withstand the imposed environment (design goal environment). This proportion will always remain unknown unless the entire population is tested. However, this unknown proportion (p) can be bounded by confidence limits for a specified confidence coefficient (P) (e.g., 90 percent such that $p_\ell < p < p_\mu$ or $p \geq p_\ell$ in which p_ℓ and p_μ are the lower and 90 upper bounds, respectively.

i. The discussion in paragraphs 3-4 *e* and *f* regarding α and β are also applicable to binomial distributions. The basic approach (Mace, 1964) is summarized below.

j. The hypothesis to be tested is H_o: $p > p_o$, where p is the true but unknown proportion of successes in the population and p_o is the least favorable value that is acceptable. As before, α is the probability of rejecting H_o when actually it is true, and β is the probability of accepting $p \geq p_o$ when actually $p = p_1$, where $p_1 < p_o$

Let: n = Number of tests in sample
s = Number of successful tests

Define:

$$m = \frac{\ell n \frac{1-p_o}{1-p_1}}{\ell n \frac{P_1}{P_o} + \ell n \frac{1-p_o}{1-p_1}} \qquad (3\text{-}13)$$

$$h_o = \frac{\ell n \frac{\beta}{1-\alpha}}{\frac{P_1}{P_o} + \frac{1-p_o}{1-p_1}} \qquad (3\text{-}14)$$

$$h_1 = \frac{\ell n \frac{1-\beta}{\alpha}}{\ell n \frac{P_1}{P_o} + \ell n \frac{1-p_o}{1-p_1}} \qquad (3\text{-}15)$$

Then
Accept H_o: $p \geq p_o$ if $s \geq h_o + nm$.
Reject H_o: $p \geq p_o$ if $s \leq h_1 + nm$.

Conduct an additional test if
$h_1 + nm = < s < h_o = nm$

Example:

Problem: Test the hypothesis: H_o:$p \leq (p_o = 0.90)$ for $\alpha = 0.10$.

Let $p_1 = 0.70$ and $\beta = 0.30$

(*Note*: $\beta = 0.30$ implies that there is not much concern about accepting $p \geq 0.90$ when actually $p = 0.70$. If there is concern, choose $\beta \leq 0.05$.)

Data:
$n = 5$
$s = 4$

$$m = \frac{\ell n \frac{0.1}{0.3}}{\ell n \frac{0.7}{0.9} + \ell n \frac{0.1}{0.3}}$$

$$m = \frac{-1.0986}{-0.2513 + (-1.0986)} = \frac{-1.0986}{-1.3497} = 0.814$$

$$h_o = \frac{\ell n \frac{0.3}{0.9}}{-1.3499} = \frac{-1.0986}{-1.3499} = 0.814$$

$$h_1 = \frac{\ell n \frac{0.7}{0.1}}{-1.3499} = \frac{1.9459}{-1.3499} = -1.442$$

$h_1 + nm = -1.442 + (5 \times 0.814) = 2.628$
$h_o + nm = 0.814 + (5 \times 0.814) = 4.884$
$2.68 < s = 4 < 4.884$

The data show that $h_1 = nm < s\ h_o + nm$. Therefore, an additional test must be conducted to verify the hypothesis at the α and β probabilities selected.

For
$n = 9$
$s = 8$
$h_o + nm = 0.814 + (9 \times 0.814) = 8.140$
$s < h_o + nm$
$s < h_1 + nm$

For
$n = 10$
$s = 9$
$h_o + nm = 0.814 + (10 \times 0.814) = 8.954$
$s < h_o + nm$

Accept H_o:$p \geq 0.90$

Thus it would take 10 tests with 9 successes to be

able to assert that p $\geq$0.90, with a confidence of 90 percent, that the hypothesis will be accepted when it is true, and with a probability of 0.3 of accepting the hypothesis when actually p could be as low as 0.70.

k. Figure 3-5 shows plots of the functions (h_1/n) +m and (h_o/n) +m for values of n for p_o =0.90, α=0.10, and β =0.25. The curves are developed from equations 3-10 and through 3-14 and can be used as follows.

l. Select a value of p_1 that is desired for the analysis and calculate p_1/p_0. From the (h_0/n) +m set of curves, find the value of s/n required for acceptance of H_0:p$\geq p_0$ for the desired n. From the (h_1/n) +m set, find the value of s/n that would require rejection of H_o for the desired n.

Example:

Let p_1=0.70

p_1/p_0=0.78 (P_0=0.90)

Accept H_0:$p_0\geq$0.90 when		Reject H_0:$p_0\geq$0.90 when	
n	s/n$\geq$	n	s/n$\leq$
10	0.91 (10 10)	10	0.66 (6/10)
7	0.94 (7/7)	7	0.60 (4/7)
5	1.00 (5/5)	5	0.52 (2/5)
4	1.05 --	4	0.44 (1/4)
3	1.12 --	3	0.32 (0/3)

The above data show the following:

— For p_o =0.90, p_1 =0.70, α =0.10 and β =0.25, it is impossible to verify the hypothesis with fewer than 5 tests, i.e., it is impossible to have s>n.

For a sample of 5, all tests must be successful to accept H_0:p$\geq$0.90

As tests are conducted, the criteria for rejection can be constantly monitored; for example, if after 4 tests, 3 have failed (s =1, s/n =¼), the hypothesis must be rejected for the parameters selected above.

Problem: What is the proportion (p) of systems that will survive the design-goal test environment with an associated confidence coefficient of 90 percent? Thus we must find p such that p $\geq$P with a confidence of 90 percent.

Data: n =3 (tests conducted at the design-goal level)
r =2 (minimum number of successful tests)

From table A-2, column (n =3, r =2), find the value nearest to 0.10 (0.10 =1.0 - 0.90). The value is 0.104. In the p column read the corresponding value, which is 0.20. (Note: the table values can be interpolated if desired to get the value of p for exactly 0.10.) This value (0.20) is p . The confidence interval is p $\geq$0.20 with an associated e confidence coefficient of 0.90. The statement can now be made (based on the test data) that the proportion of successes to be expected in the population is greater than or equal to 0.20 and there is a 90 percent confidence that this is true.

m. When the system manager assumes a priori, what constitutes an acceptable confidence interval and when the computed interval seems too low, two alternatives exist: Conduct more tests with the expectation that some of those tests will be successful, or decrease the expectation of the confidence limit and accept the greater risk. For example, if two or more tests are conducted and both are successful, then

n =5
r =4

From table A-2, the 90 percent confidence limit is:
p$\geq$0.42

If no additional tests could be conducted, a lesser confidence must be accepted to decrease the interval or increase p. For

n =3
r =2

and a 70 percent confidence, the confidence limit is:
p$\geq$0.37

For 50 percent confidence, the confidence limit is:
p$\geq$0.50

The results of this example support the observations of the previous section, i.e., it is impossible to make high confidence statements with a meaningfully narrow confidence interval without conducting a significant number of tests (even if all tests are successful). This is further demonstrated by the curves in figure 3-6.

Figure 3-5 Determination of Minimum Sample Size

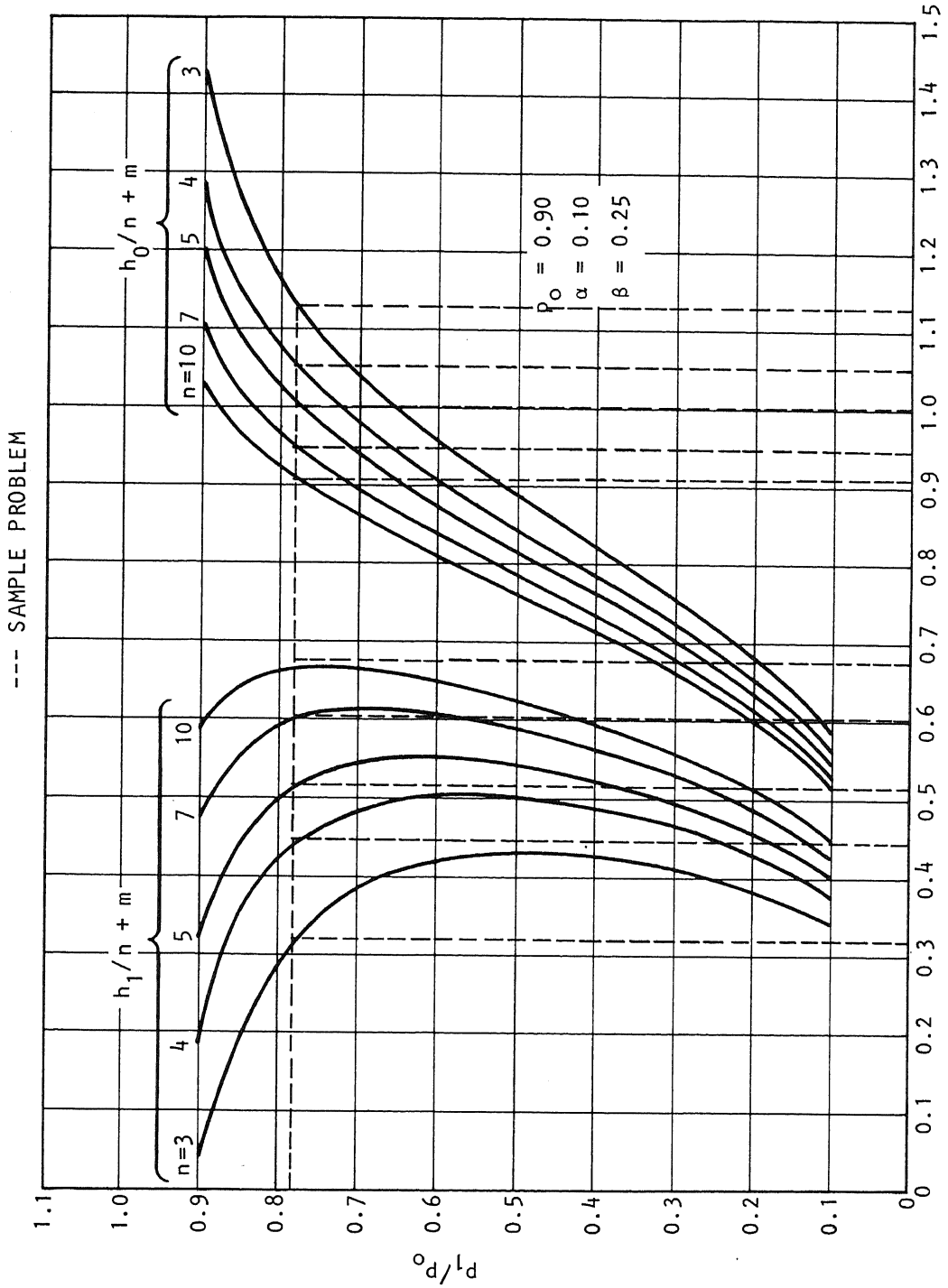


FIGURE 3-5. DETERMINATION OF MINIMUM SAMPLE SIZE (p_1/p_o vs. s/n)

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CHAPTER 4
VERIFICATION REQUIREMENTS AND EXPERIMENTAL METHODS

4-1. Introduction.

a. In verifying whether systems will survive a postulated nuclear attack, both experimental and analytic (mathematical) methods may be required. The selection of the methods to be implemented is the responsibility of the systems manager and the verification analyst. The decision is based on system design and mission requirements as well as on:

—Accuracy of mathematical models
—Cost of calculations
—Accuracy of experimental simulation of environments
—Cost of experiment
—Number of items available for analysis

b. Although protective and protected systems must be capable of withstanding the 13 weapon effects described in TM 5-858-2. each system will be more susceptible to some effects than to others. If the facility and its contents are resistant to particular effects, the system is defined as super-hard with regard to those effects, and verification will not be required. Conversely, some systems may be very susceptible to some effects, and redesign rather than verification is required. It is primarily toward those systems whose survivability is marginal that the verification program is directed.

c. Verification studies must consider the free-field weapon-effect load, the local load at the system, subsystem, or element level via the transmission path between the free field and the local load point, and the resistance of the system in question. System managers must define the free-field weapon-effect load, the transmission path characteristics, and the system resistance probabilistically, i.e., in terms of their mean values and their coefficients of variation (COV's). In general, a deterministic assessment of hardness will not be acceptable.

4-2. Simulation requirements.

a. Definition of the local environments that excite systems, subsystems, and elements is a significant effort that must be accomplished to provide input to the verification analysis. Although it may not always be the case, the verification analysts likely will inherit responsibility for defining local loads, since they have access to the data from which input loads would be derived and they are in the best position to understand the true nature of those environments.

b. The transmission of the primary weapon-effect loads from the free field to the input points of the systems is highly dependent on the threat (weapon size and number, height or depth of burst), the siting conditions (geology), and the configuration of the facility. The general characteristic of the free-field nuclear weapon effects are presented in TM 5-858-2. Although it is not practical to present a comprehensive discussion of the methods for simulating the transmission of the particular weapon effect from the burst point to the hardened target, a recommended methodology is presented in chapter 6.

c. The system/weapon-effect combinations of protective system for which hardness assessment must be accomplished are presented in table 4-1. It must be recognized that each of these systems will contain numerous subsystems and elements. In many instances it will be necessary to perform the verification analysis at the element or subsystem level. For each separate item to be analyzed, specific requirements and methods will need to be defined. Simulation requirements and techniques must be fully developed, evolving finally into a comprehensive test and analysis plan to guide the conduct of the analysis.

d. Protected systems must also be subjected to hardness verification. These systems are not separately addressed in this manual. However, in most cases they must be hardened only to the local environment within the protective structure or on the shock-isolation system.

e. Experimental techniques are used to generate input that simulates the overpressure, ground shock, and EMP nuclear weapon effects for verification analyses. Exclusion here of techniques for the other effects presented in TM 5-858-2 does not imply that these effects can be ignored. The susceptibility of each subsystem to all effects must be determined and verification testing conducted if necessary. However, in general the subsystem design(s) will be governed by these three weapon effects. The GE-TEMPO (1972) and Bednar (1968) reports present detailed information for some of the techniques that were in use in 1972 and 1967, respectively. Excerpts from both are presented in appendix B.

Table 4-1 Protective Systems: Requirements for Weapon-Effect Hardness verification

Protective System \ Weapon Effect	Initial Nuclear Radiation	Electromagnetic Pulse	Fireball	Thermal Radiation	Overpressure	Overpressure-Induced Ground Shock	Ground-Shock	Crater-Induced Ground Shock	Crater	Ejecta/Debris Impact	Ejecta/Debris Depth	Dust	Firestorm	Residual Nuclear Radiation
Structures Aboveground and Semiburied	X			X	X	X								
Flush Buried and Shallow Buried	X	X		X	X	X	X		X	X			X	
Deep Buried							X							
Shock Isolation						X	X							
Air Entrainment	X	X	X	X	X	X	X	X	X	X	X	X	X	
Mounts and Fastenings						X	X							
Hydraulic Surge						X	X							
EMP Shielding		X			X	X	X							
Radiation Shielding	X				X	X	X						X	
Thermal Shielding and Fire Barrier			X	X	X	X	X							X

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4-3. Simulating and testing overpressure.

Design. The airblast environments will have extreme variations. Surface/flush structures/ systems or the surface elements of air-entrainment systems may be designed to survive peak overpressures of 1000 psi and greater, whereas aboveground facilities may only be required to survive tens of psi or less. No single technique or tool is adequate to providing the simulation-testing capabilities required for verification throughout this range.

(1) Because large field tests usually are provided by a central agency, involve numerous other agencies, and may be available only once during the total verification process for a particular facility, the opportunity should be optimized. This means that the resistance of all critical elements of the system or subsystem to be tested must be estimated beforehand with corresponding uncertainties. Furthermore, the incorporation of these resistances into a complete system, as described in chapter 6, must show a high probability that the system will survive. The system is then fielded such that the design environments are simulated as closely as possible. Replication of the tested system at different ranges from ground zero is very desirable in order to acquire data above and below the design environment.

(2) It is most important that the actual local load inputs and the failure-mode responses be accurately measured to provide results of high statistical confidence that will credibly support a final post-test verification statement. Depending on the degree of simulation achieved for the environments of interest, it may be necessary (as discussed above) to base the final verification statement on a calculation from a verified mathematical model.

b. High-explosive simulation technique (HEST) tests. The basic configuration of a HEST test is illustrated in figure 4-1. A cavity is constructed over the test item. The amplitude of the peak overpressure is controlled by the density of explosives, generally Primacord, in the cavity. The positive-phase duration is governed by the depth of the surcharge, and the propagation velocity is governed by the wrap angle of the Primacord.

(1) Combustion products of the Primacord are released at a rate that is proportional to the Primacord wrap angle. These products act as a piston to drive a shock wave into the undisturbed cavity volume. As the generated pressure acts against the overburden, the cavity volume increases as the overburden rises, causing the prssure amplitude in the cavity to decay. It is this process that produces the fast rise and exponential decay to simulate the nuclear overpressure.

(2) A HEST test can be configured to produce a blast wave that provides, for short durations, good simulation of the overpressure from weapons that extend up to the megaton range. Because of the limited duration that can be simulated, stress attenuates in the ground more rapidly with depth than for the nuclear event and the displacements will be smaller. Hence, the early dynamic responses of the tested system will approach those that would be induced by the nuclear event, and good simulation of peak accelerations and velocities is achieved; but late-time rigid body motions are not well simulated.

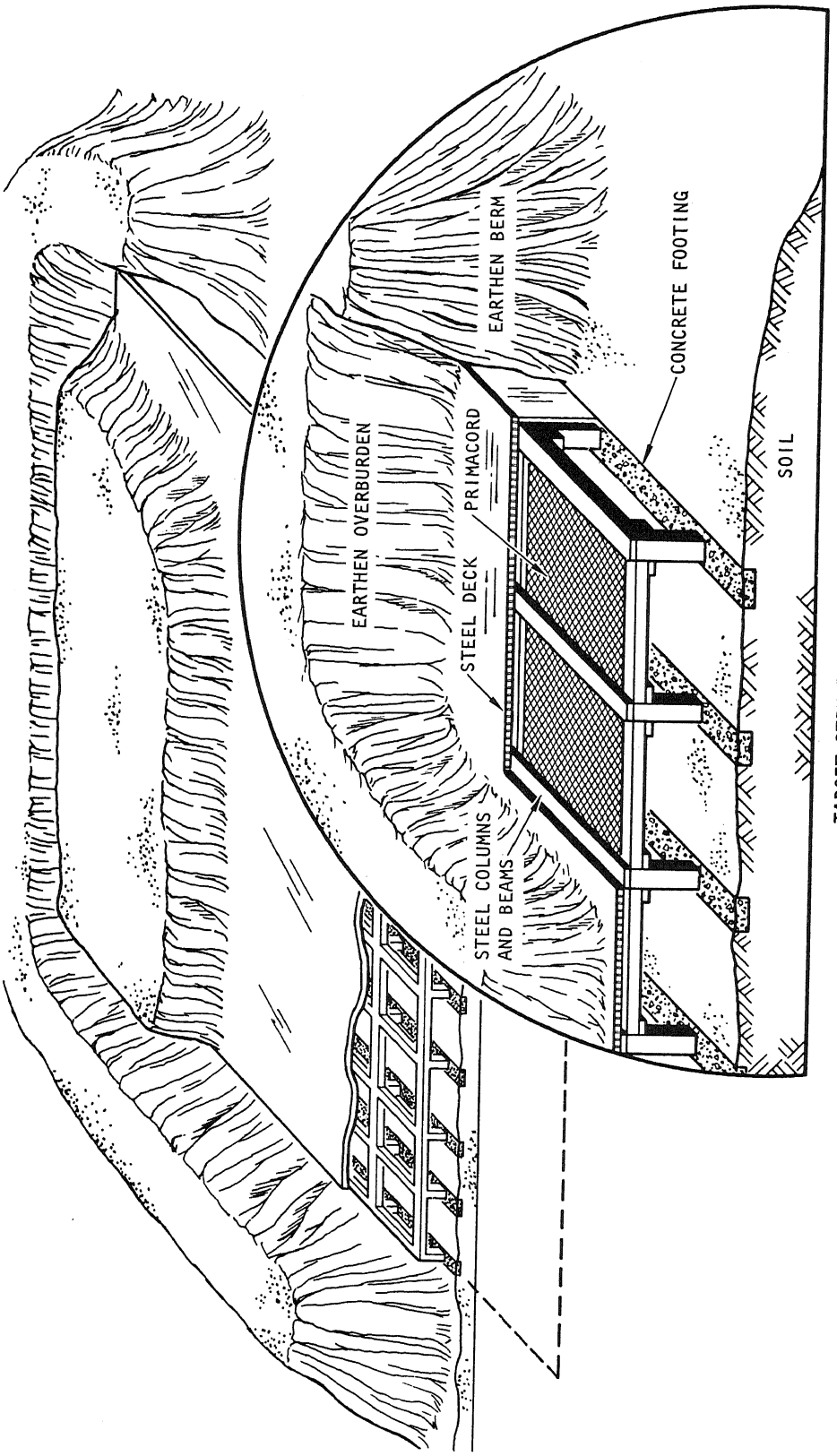
(3) The technique is applicable primarily for testing surface-flush and shallow-buried structures where the principal failure mode considered is directly related to overpressure loading. Dynamic pressure effects are not well simulated by the HEST test, and failure modes related to this effect must be tested separately. Because the peak overpressure is essentially the same over the entire test area, specimens of large dimensions can be realistically loaded in a HEST test. Both full-scale and model structures can be tested in the HEST test bed.

(4) Even though the positive-phase duration does not simulate the nuclear event at late times, the duration is usually sufficient to provide adequate loads for direct verification when the overpressure impinges directly on the test item. Thus, good verification data can be obtained for most deformational failure modes for surface-flush systems such as structures and closures. Further information on HEST is available in D'Arcy et al. (1965), D'Arcy-Clark (1966), GE-TEMPO (1972), and ble Traindafilidis-Zwoyer (1968).

c. High explosive (HE) field tests. Many HE tests have been conducted to provide overpressure and ground-motion environments in sizes varying from a few hundred pounds to hundreds of tons of equivalent TNT. For overpressure studies the explosives are placed in spherical or hemispherical arrangements at or above the earth surface, typically as shown in figure 4-2.

(1) The blast wave produced in an HE test provides good simulation of the peak amplitude for both the overpressure and dynamic pressure. The peak pressure amplitudes from an HE burst decay more rapidly with distance from the center of the charge than do nuclear bursts because usually less weapon yield is available. Because of this, only the

Figure 4-1. Sketch of HEST Facility



larger tests (e.g., 500 tons) are adequate for testing full-scale elements. For large systems, the system-size/peak-pressure combination of interest will generally dictate that testing be performed on models of subsystems. Certain elements such as closures and blast valves may be subjected to good simulation of peak loads for direct verification.

(2) HE tests provide an airblast environment that is comparable to the nuclear environment especially at peak overpressures below 300 psi. Good simulation of overpressure is provided for a wide range of yields but particular attention must be directed to proper scaling. The yield dependence is discussed in chapter 7 of TM-5-858-2. Further information on HE tests is available in Kingery (1968) and in Reisler et al. (1975).

d. Airblast simulators. In addition to the large-scale field tests described above, there are fixed facilities designed to produce blast waves that simulate to some degree the blast wave from a nuclear event. Many of these facilities are listed in appendix B and are useful for component or element testing. Two of the larger facilities of this type are GRABS and LBLG, described below.

e. Giant reusable airblast simulators (GRABS). The GRABS facility is located at the Kirkland AFB and is operated by the Air Force Weapons Laboratory (AFWL). The basic configuration of the GRABS facility is shown in figure 4-3. The facility provides for a soil depth of up to 30 feet for emplacement of the specimen to be tested. The amount of explosives, cavity volume, and soil surcharge depth are selected to produce the pulse desired within the range of the facility capabilities. The mechanism of producing the pulse is similar to that of the HEST test except that the pressure pulse does not horizontally traverse the specimen but loads are areas of the test bed simultaneously and essentially equally. Simulation of the peak overpressure history is similar to that achieved in a HEST test. The size of the facility allows for testing of full-scale elements; subsystems and systems would generally be modeled for testing. The test s design must consider the reflecting boundaries of the facility. The s response time(s) of the failure mode being studied must be such that the critical parameters have reached peak amplitudes before reflected waves reach the location of interest. Further information on GRABS is available in Bartel and Jackson (1973) and Jackson et al. (1973).

f. Large blast load generator (LBLG). A number of blast load generators listed in appendix B and discussed by GE-TEMPO (1972) and Bednar (1968), of varying sizes and designs have been used to conduct verification tests on full-scale elements and models of elements and subsystems. One of the largest of such facilities is the Large Blast Load Generator (LBLG) located at the U.S. Army Engineer Waterways Experiment Station (WES). The basic configuration of the LBLG is shown in figure 4-4. Further information on LBLGs is available in Albritton (1965) and in Kennedy et al (1966).

(1) A soil bed of up to 10 ft deep can be loaded for emplacement of specimens to simulate buried conditions. Peak pressure and positive phase durations can be controlled within the range of the facility capabilities. Durations equal to or exceeding those from megaton nuclear events can be achieved.

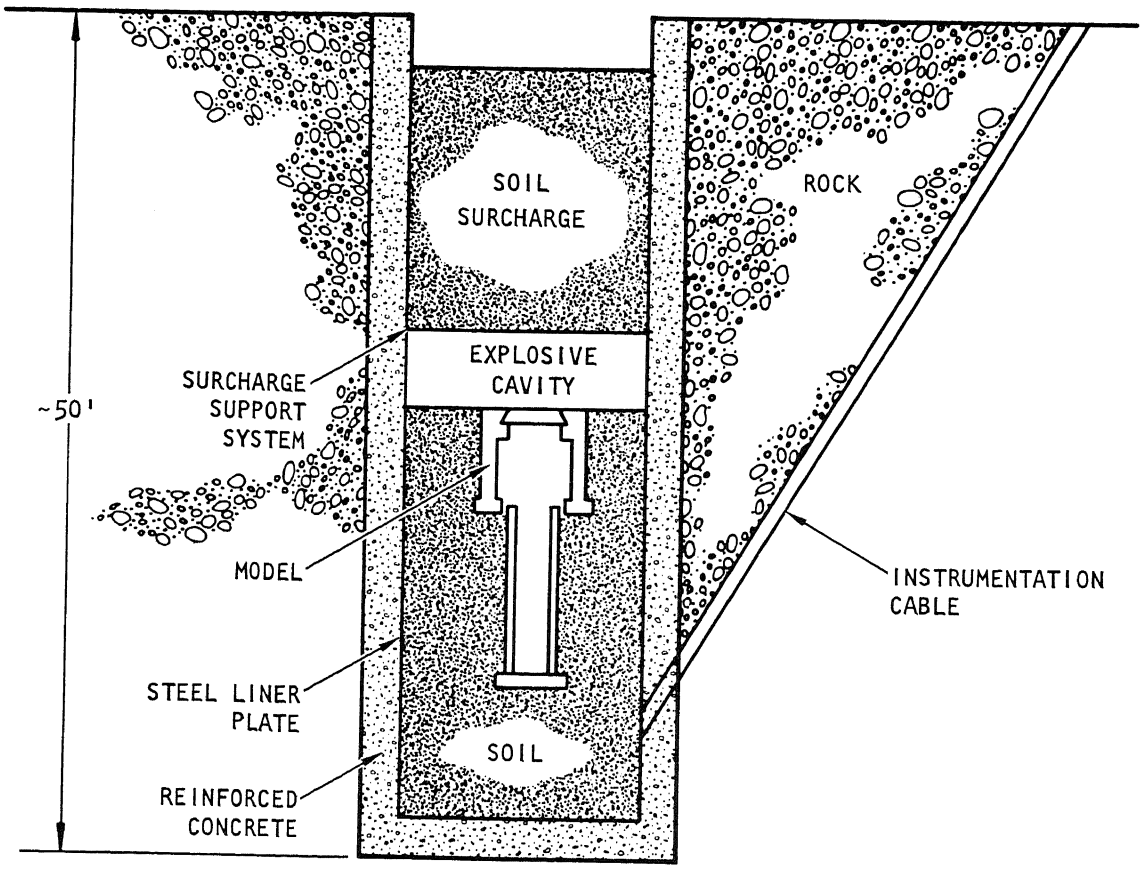
(2) Airblast loads for elements and subsystem models can be provided to accurately simulate nuclear effects. As with the GRABS facility, the test must be designed such that reflections from the facility boundaries will not affect the failure mode response being studied until maximum amplitudes have been reached.

g. Shock tubes. A number of shock-tube facilities are listed in appendix B and discussed by GE-TEMPO (1972) and Bednar (1968). In general, such facilities provide a good simulation of the airblast characteristics of a nuclear event, namely peak overpressure, decay rate, positive-phase duration, and dynamic pressure. Shock tubes are used for testing subsystem models and small full-scale system elements. However, depending on the response of the failure mode being studied, verification can be accomplished through scaling. Direct full-scale verification testing of the performance of air-breathing equipment can also be accomplished in shock tubes. Shock tubes have also been used to perform debris-impact tests. Further information on shock tubes is available in Lane (1971).

4-4. Simulating and testing ground shock.

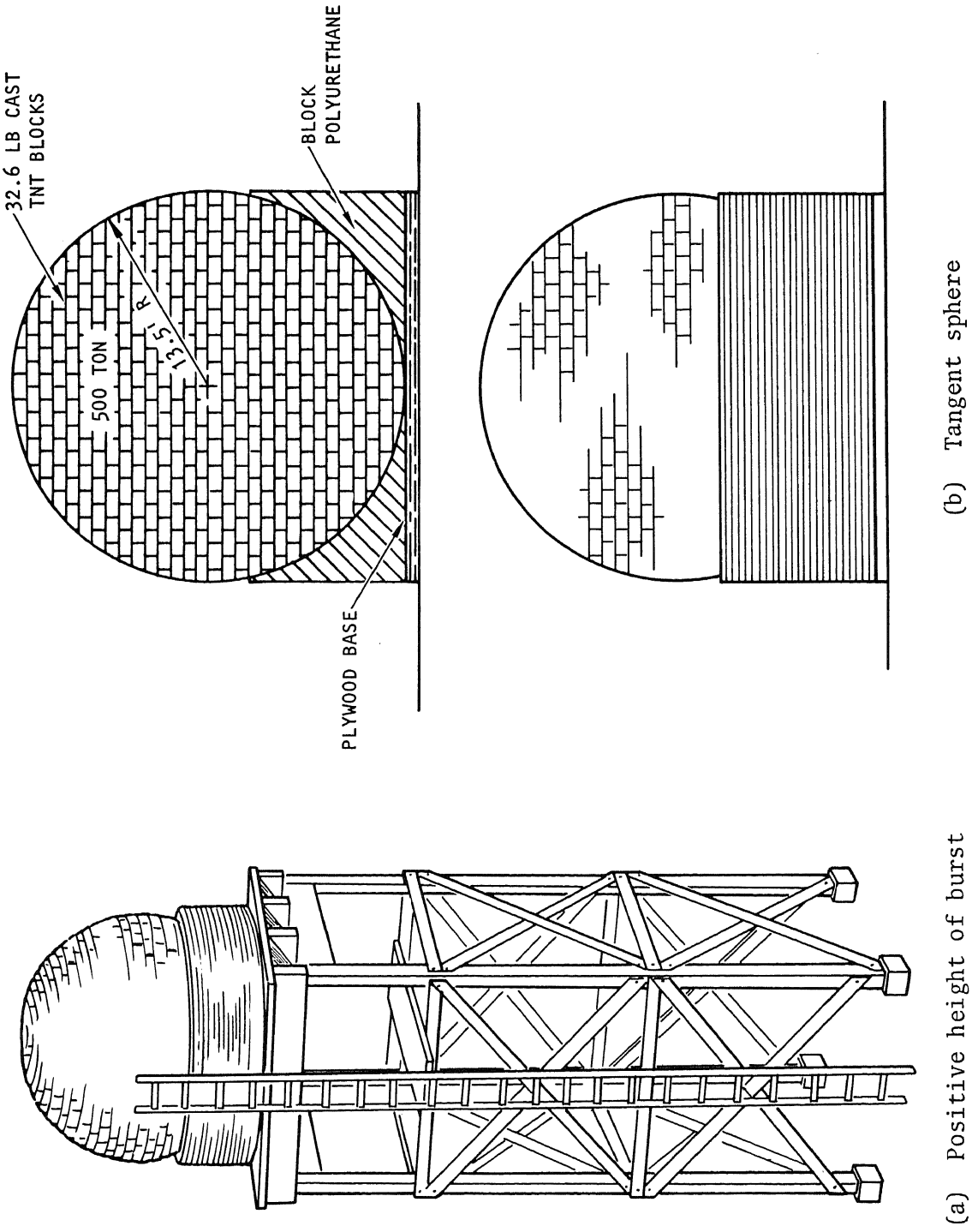
a. Overpressure-induced and crater-induced. The techniques and facilities that are used to simulate the ground-shock environment from a nuclear event are the same whether the shock is induced from the overpressure or the crater formation. The environments, motion and stress, created by the two sources are very different as presented in TM 5-858-2, and are dependent on combinations of weapon nt size, height or depth of burst, and surrounding media. Some of the tests t described above for simulation of overpressure are also used for ground shock. It is generally the objective, particularly when testing full-scale subsystems or elements, to simulate the airblast and ground shock

Figure 4-3. The Giant Reusable Airblast Simulator (GRABS)



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Figure 4-2. Typical HE Field Test Configuration (Spherical Charge)

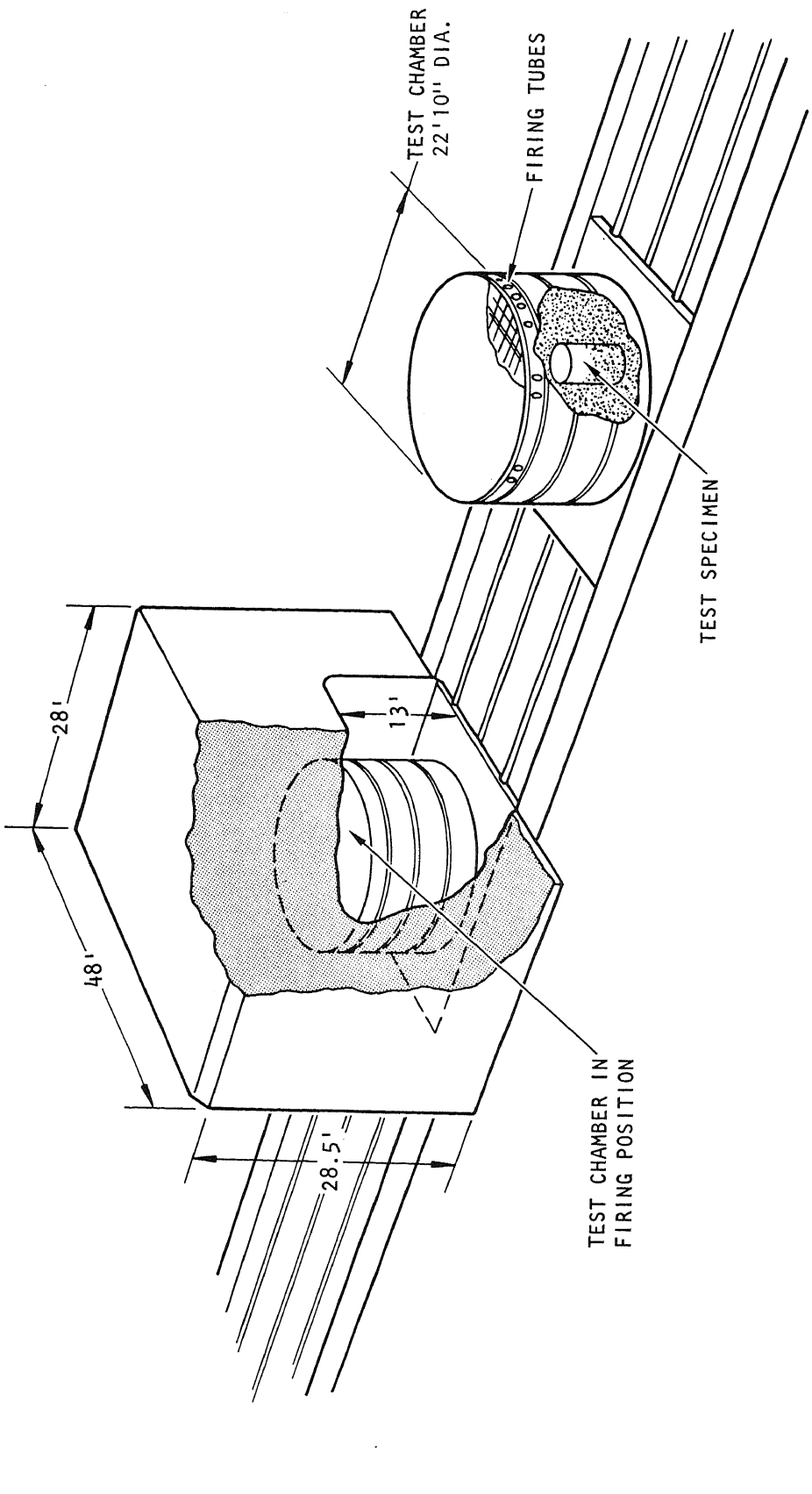


(a) Positive height of burst

(b) Tangent sphere

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Figure 4-4. Large Blast Load Generator (LBLG)



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simultaneously. Only in rare circumstances is this actually accomplished. Usually one environment or the other must be compromised. Whether overpressure or ground shock is most important is a decision that must be made by the verification analyst. The decision is based on the susceptibilit of the failure mode(s) being studied to the particular design environments. Many times, separate tests will be required to achieve complete verification of the system.

b. HEST test. The HEST test described above for simulation of overpressure is one of the best techniques for studying overpressure-induced vertical ground motion over relatively large areas. However, as with all simulation techniques, a completely satisfactory simulation cannot be achieved.

(1) Because of the complex geometry of the test facility and the relatively small surface on which the pressure load acts, the ground motions that occur in a HEST test probably are more complex than comparable responses in a nuclear environment. The HEST test does not simulate all aspects of nuclear ground shock; because of the finite dimensions of the test cavity "edge effects" distort the measured response.

(2) Analyses performed for HEST programs indicate that, in some regions beneath the test bed, peak vertical and horizontal-longitudinal (in the direction of the blast-wave propagation) accelerations, velocities, and stresses are reached before edge-induced (relief wave) responses can influence overpressure-induced responses. Figure 4-5 shows these regions. The analyses also show that the peak displacements, which occur late in time and include edge effects, do not simulate nuclear responses. Other responses, such as the horizontal-transverse (perpendicular to the direction of the blast-wave propagation) and beneath-berm motions, are also HEST-unique and have no direct relationship with the nuclear problem.

c. High explosive (HE) field tests. HE field tests designed to simulate overpressure also produce ground shock. However, the limited yield of the HE device usually precludes testing of items other than elements or models. Moreover, ground motion is critically dependent on the geology, so it is difficult to locate an HE test site that scales geologically to an operational site.

(1) The predominance of one motion over the other (overpressure-induced and crater-induced) depends on the different attenuation rates and consequently on the distance from ground zero where motion is measured, and on the particular motion parameter considered and the associated direction. Overpressure may dominate the acceleration at all ranges of interest to this volume except deep-based systems. However, the crater-induced accelerations may cause larger maximum displacements. In general, overpressure-induced motions will contain higher frequency components than the crater-induced motions, especially near the ground surface.

(2) The familiar HE test configuration shown in figure 4-2 is not effective in simulating the crater-induced ground-motion weapon effects. To circumvent this, special configurations of charge burial are used as shown in figure 4-6. Using finite element computer codes, the configuration of the charge is calculated for the particular geology, yield, and HOB/DOB combination of the nuclear weapon to be simulated. This technique produces good simulation of the crater-induced motions but does not simulate the overpressure. At this time (1976), accurate verification of both effects cannot be achieved in a single test event. Further information on HE tests is available in GE-TEMPO (1967, 1970, 1973), Stubbs et al. (1974), and Rooke et al. (1974 and 1976).

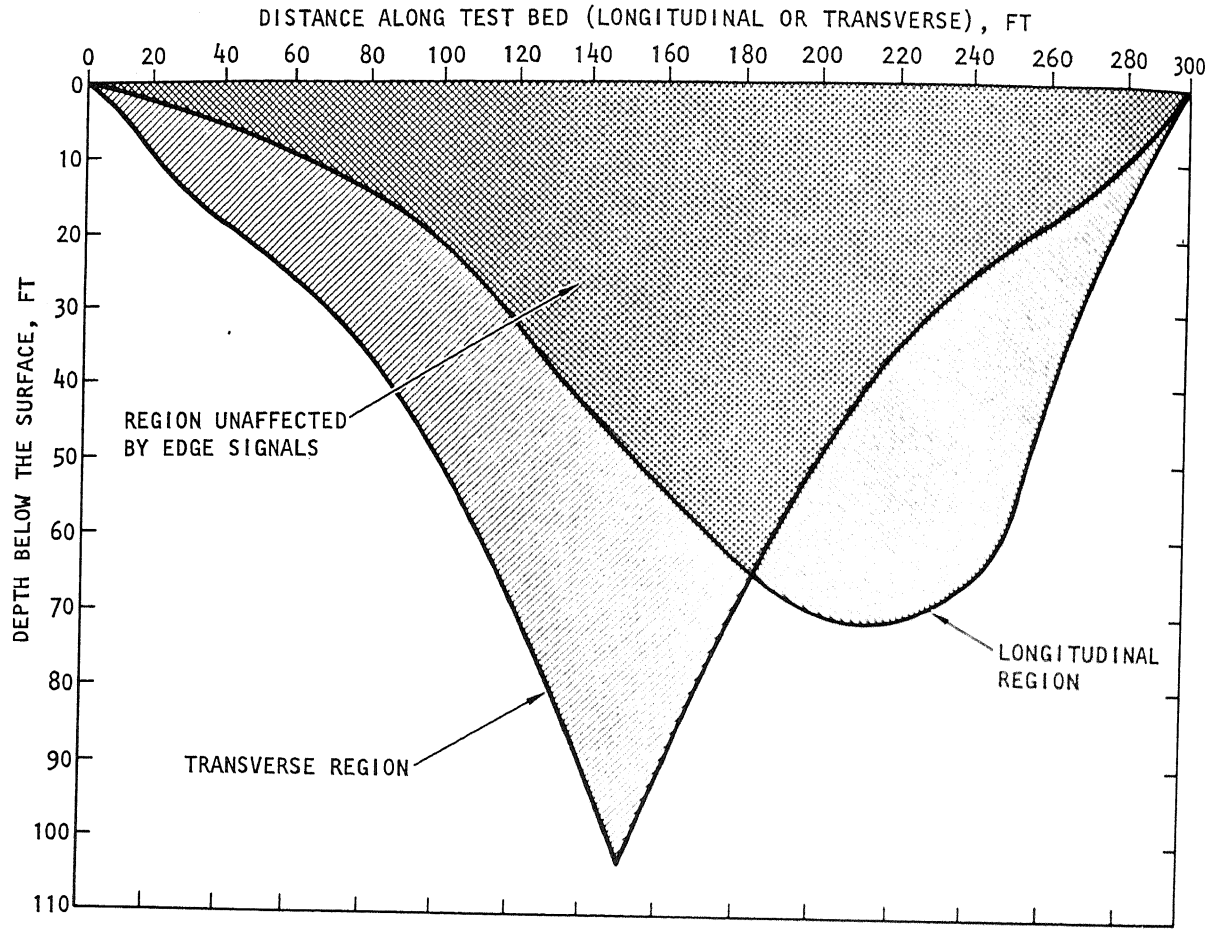
d. HEST-BLEST. The HEST test is limited in effectiveness by the size of the test bed/cavity; the HEST-BLEST concept shown in figure 4-7 was developed to overcome this deficiency. Here, the HEST cavity is constructed over a relatively small area where it is necessary to produce the overpressure directly on the surface of the structure system. Separate shallow-buried, high-explosive charges are then placed in a much larger surrounding area. This technique of loading the area is called a Berm Loaded Explosive Simulation Technique (BLEST).

(1) The BLEST charge array is designed to simulate the stress environment in the upper surface of the test area that would result from nuclear overpressure loading. This loading combined with the direct air-blas from the HEST cavity simulated the overpressure from a nuclear s event over a much larger area and for much larger times than in a simple HEST test. The peak displacements are not influenced by the unloading waves from the edge of the HEST cavity.

(2) This test does not simulate crater-induced ground shock. Further information on HEST-BLEST is available in Schrader et al. (1976).

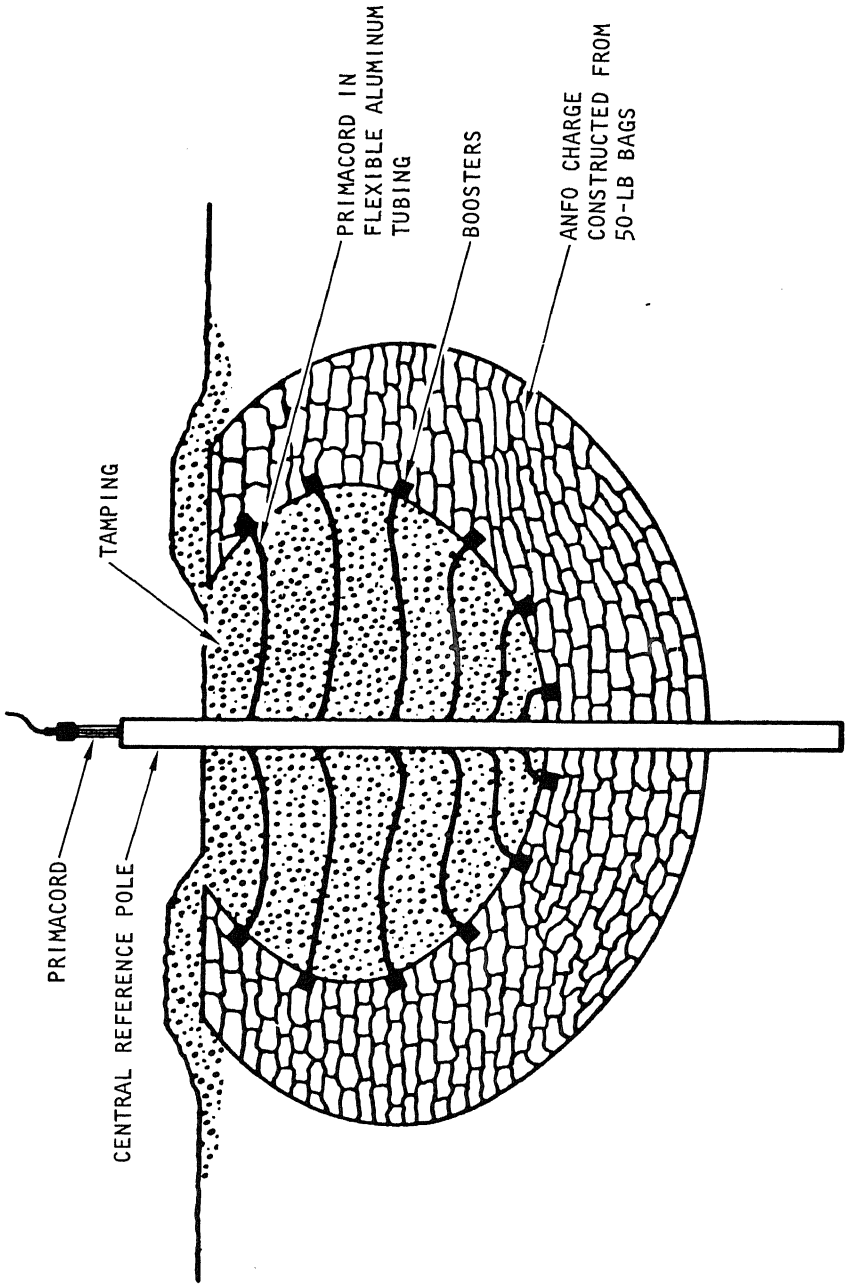
e. HEST-DIHEST. As evidenced by the above discussions on HEST and HE tests, there is no single technique that produces a totally satisfactory simulation of both the overpressure-induced ground shock and the crater-induced ground shock

Figure 4-5. Regions under Test Bed where Peak Vertical Velocity, Stress, and Acceleration can be Attained Without Edge Interference.



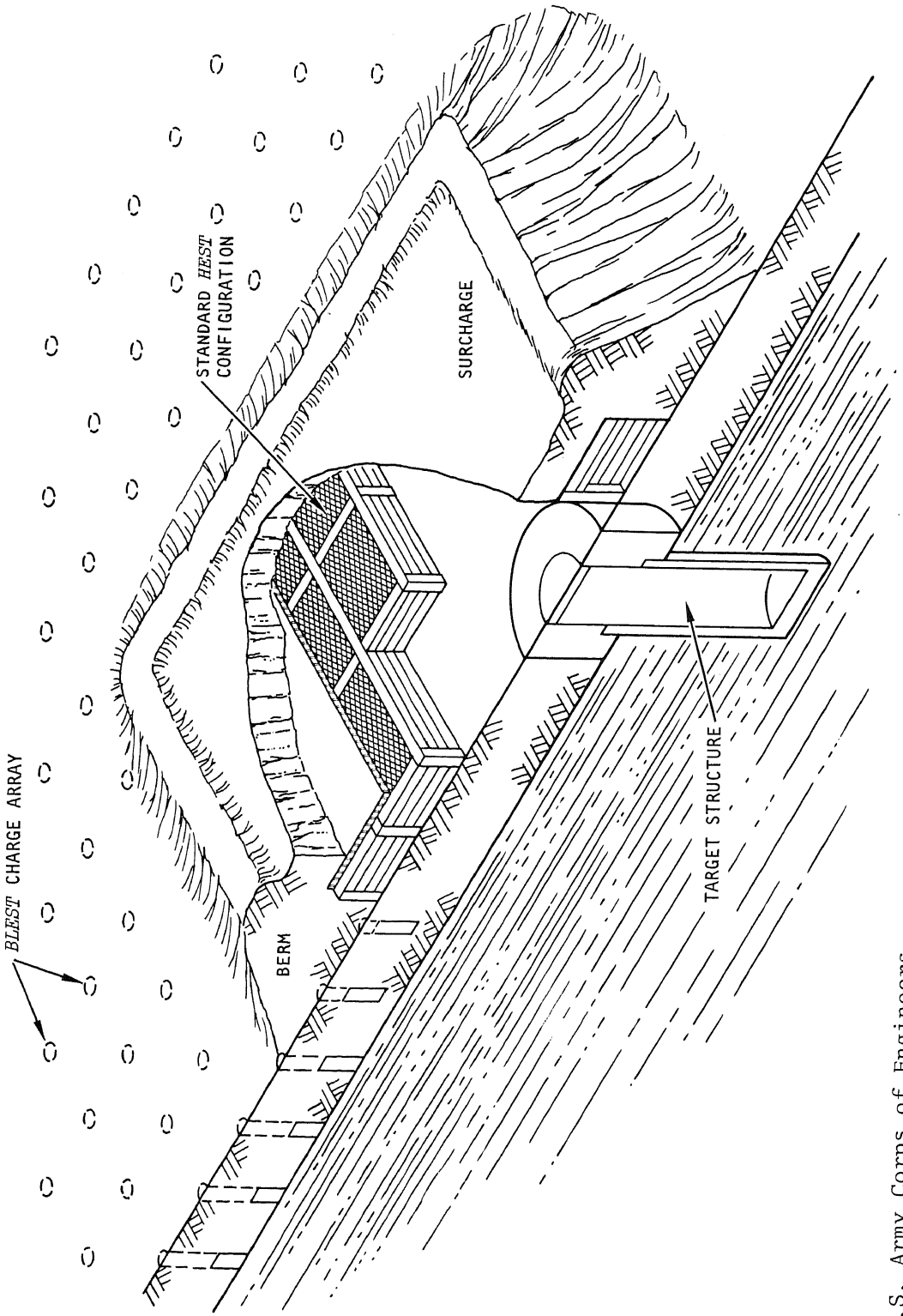
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Figure 4-6. HE Test Configuration to Simulate Crater-Induced Ground Shock



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Figure 4-7. HEST/BLEST T Configuration



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ffects. Therfore, tests have been designed that ombine the HEST test with DIHEST Direct-Induced High-explosive Simulation echnique) to produce both effects simultaneously.

(1) The basic configuration of a typical HEST-)IHEST test is shown in figure 4-8. This test is esigned to combine overpressure and limited round shock from the HEST test with crater-ıduced ground shock from the DIHEST test. The)IHEST test uses a buried array, usually planar, f high explosives that are detonated multaneously, to produce a predominately hori-)ntal shock wave on a test system. Timing of the etonation of HEST and DIHEST explosives sys-ems and location of the DIHEST array require xtensive pretest experiments and calculations.

(2) Tests have been conducted in both rock and)il media. The size of the HEST cavity, as well as ıe design of the DIHEST array, influences the ıration over which the ground motion is simu-.ted. Generally acceptable simulation of accelera-on, velocity, and stress peak amplitudes are ac-eived.

(3) Further information on HEST-DIHEST is vailable in Schlater (1972) and Blouin (1969).

f. Mechanical tests. The tests discussed for the mulation of overpressure and ground shock apply) scale model and full-scale testing of systems and ıbsystems. However, before field or large-scale .boratory tests are conducted, and before a system as been fabricated, comprehensive testing will be erformed on elements and small subsystems. hese tests, conducted to obtain data for basic evelopment and verification, are mechanical tests, . which the excitation force is applied directly to ıe specimen through a known mechanical connec-on.

(1) Mechanical tests are generally the simplest ıd least expensive to conduct; the specimens are latively small (i.e., measured in feet rather than ns or hundreds of feet), and the test equipment is adily available. Because of these factors, this pe of testing is popular, and most of the statisti-ıl data to determine the mean resistance and ıcertainty associated with a particular failure ode will be acquired with these tests.

(2) The greatest limitation of the mechanical st is that it is not directly comparable to the ee-field weapon-effect ground shock. Therefore, it necessary that supporting analyses and tests ften very complex and costly) be conducted to anslate the free-field ground shock to the local put environment. Nevertheless, compared to the unwieldy field test and the large-scale laboratory test, the mechanical test will generally be the most used tool in the verification process.

(3) There are numerous techniques and facilities used to conduct mechanical tests. A discussion of some of the most applicable facilities is presented in appendix B and in GE-TEMPO (1972) and Bednar (1968). However, in many instances it will be necessary to apply basic force-producing equipment such as shakers or rams, in a manner that is unique to the element-input requirement combination being addressed, and no existing fixed facility would be adequate.

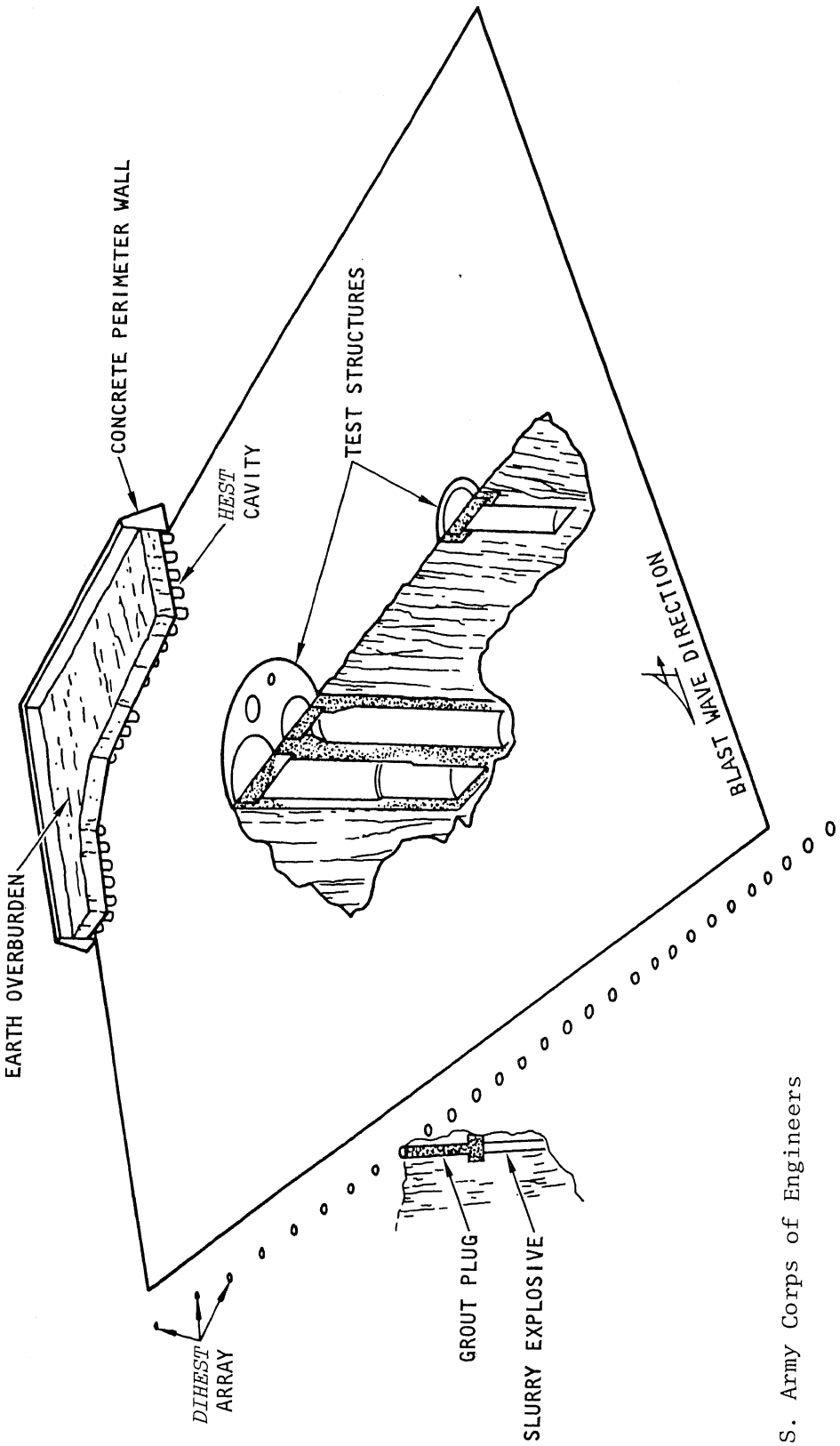
(4) In many instances it will be required to perform a verification test of a large subsystem in a full-scale operational mode (e.g., of critical control and communication equipment supported on a shock-isolated floor or platform). In such cases, where fixed-facility tests are prohibitively costly, pulse-train simulation tests have been conducted for verification. This technique applies specifically designed force-pulse trains at the required number of locations, directly on the platform structure, such that the platform response simulates the response experienced by the total shock-isolated system as a result of the motion induced in the protective structure by the ground shock. The technique uses measurements of impedence and transfe functions on the as-built, in-place subsystem to transfer the motion from the attachment point of the protective structure to critical locations on the platform. With the equipment elements in place, these motions are then simulated on the platform by application of the force-pulse trains.

(5) Further information on mechanical tests is available in Safford and Walker (1975a and b).

4-5. Simulating and testing EMP.

a. Uniqueness. The waveform and corresponding frequency spectrum for a nuclear EMP differ significantly from other man-made electromagnetic disturbances or from natural phenomena such as lightning. The pulse rises very rapidly (nanoseconds) to the maximum level (hundreds of kilovolts per meter for the electric field) and then decays exponentially. The frequency range is extensive, varying from UHF to VLF. Also, the EMP field is widely distributed, whereas g lightning is localized. Because of these characteristics and differences, designing to protect against EMP or to simulate for verifying hardness requires EMP-unique approaches. The verification of EMP hardness will us both analysis and testing techniques.

Figure 4-8. Typical HEST/DIHEST Test Array.



b. Verification analysis. The analysis techniques esently available are sophisticated enough to entify areas of weakness in the system design, to ıide test selection/design, and to confirm the ac- racy of test data. However, specific points of eakness and specific quantitative levels of hard- ss cannot be calculated.

c. Experimental analysis. The analysis of the stem can be accomplished using computer codes at model the many elements of the system. An perimental analysis can also be performed that nsists primarily of measuring the impendance ıd transfer functions between critical system nctions and then involving these functions in ne, or multiplying them in the frequency domain th the postulated threat environment inputs. The edicted total response will be very accurate as ng as the responses of all elements in the mea- red path remain in the linear range.

d. Verification testing. Both laboratory and field sts are conducted to provide the required simula- n for hardness assessment. Hardness evaluation r EMP may also use scale-model and component sting; however, these tests are generally not used r final verification analysis. In general, all sys- m components will be separately tested in the boratory prior to being included in a system or bsystem test, the test data being integrated. sting is used to verify calculations to confirm neral hardness of the design and identify specific eaknesses, and to provide bounds for final ver- cation testing.

c. Subthreat-level testing. Subthreat-level tests rformed on elements or on systems to define the anner in which the EMP field couples to the test em and to expose weaknesses that were not dis- vered in the analysis. Techniques used for bthreat-level testing are the following:

(1) Low-level transient: The threat time his- ry is simulated but the amplitudes are below the reat level.

(2) Repetitive pulse: A train of pulses (10 to 0 per second) is applied. The threat time history ay not be simulated, but the frequency range ust be the same as that of the threat pulse.

(3) Continuous wave (CW): A continuous wave is applied to the system. The wave may be swept across a broad frequency range or applied at discrete frequency steps.

(4) Direct injection: Any of the above signals can be directly applied at one or more parts of the systems.

(5) Stationary field: Small items are subjected to field-coupling tests.

f. Threat level. Threat-level testing requires that the simulation of the threat be applied over a volume that is large relative to the total system being analyzed. When this is accomplished, the hardness (or lack of hardness) is verified by observing selected critical system responses. Since the verification is accomplished through observation of system responses, the threat-level test environment must accurately simulate at least the following:

—Propagation direction of both the electric and the magnetic fields
—The pulse shape and frequency spectra of both fields
—Peak amplitudes greater than the threat magnitude
—Relative magnitudes of electric and magnetic fields

(1) The above requirements must be satisfied for each threat scenario for which hardness is to be verified, and the electric and magnetic fields must be developed over a volume larger than the volume of the system to be tested. The arrival direction and polarization must be addressed if total hardness is to be verified. It is also necessary that the on-line operation of the system be accurately defined such that the simulation can be imposed at the time(s) of maximum susceptibility.

(2) High-level transient field tests are required for total threat-level testing. However, some degree of verification can be accomplished at threat level using direct injection.

g. Simulation facilities. There are numerous facilities that have been developed to provide EMP simulation for various systems and components. Many of these facilities are listed in appendix B. A comprehensive treatment of EMP design and verification can be found in COE (1974) IITRI (1973), Whitson (1973), and Schlegel, et al. (1972).

CHAPTER 5
ANALYTIC TECHNIQUES

5-1. Introduction

a. The analytical approach is an important and well-established tool to support hardness verification. In situations where a physical system does not yet exist or, if it does, cannot be tested, the analytical approach may be the only way to assess hardness, survivability, vulnerability, etc. Unlike experimental verification which naturally lends itself to a statistical presentation, computational verification almost always depends on deterministic tools to provide system response to nuclear weapon effects. These deterministic tools generally produce sophisticated information of the most probable response of the system (the mean), but quantifying uncertainty will involve a laborious selection of values for the random nature of system parameters.

b. Although the design load for a system, subsystem, or element will sometimes be the input for verification analyses or tests, it may also occur that updated information will be available to better define the local load environment. Thus, the verification analyst may not only be responsible for assessing the survivability of the system to its design loads, but he may also be required to reassess the local design load to reflect more realistic conditions. Part of the reassessment will come about as a natural consequence of verification studies because the response of one system may be the load to another. Verification of the first system may indicate that the load to subsidiary system is different than expected. If the verification analyst is also charged with the responsibility for determining system survivability, he must be prepared to view the verification study from a system engineering point of view, since he will be the one most likely to intelligently assess the adequacy of previously established design criteria.

5-2. Computing uncertainties and survivability.

a. Uncertainties. The total coefficient of variation of a random variable X, designated by Ω_X is obtained from

$$\Omega_X = \sqrt{\delta_X^2 + \Delta_X^2} \tag{5-1}$$

Here, δ_X models the natural randomness of X, whereas Δ_X represents the uncertainty arising from errors in estimation. If X itself is a function of several random variables,

$$X = f(Y_1, Y_2, Y_3, \ldots, Y_n, \ldots, Y_N) \tag{5-2}$$

then using first-order linear approximations (Ang-Cornell, 1974)

$$\bar{x} = f(\bar{y}_1, \bar{y}_2, \bar{y}_3, \ldots, \bar{y}_n, \ldots, \bar{y}_N) \tag{5-3}$$

and

$$\Omega_X^2 = \Omega_X^2 + \sum_{n=1}^{N} \frac{y_n}{x^2} \left(\frac{\partial f}{\partial Y_n} \right)_0^2 \Omega_{Y_n}^2 + \sum_{n \neq m}^{N} \sum^{N} \frac{y_n y_m}{\bar{x}^2} \left(\frac{\partial f}{\partial Y_n} \frac{\partial f}{\partial Y_m} \right) \rho_{nm} \Omega_{Y_n} \Omega \tag{5-4}$$

where

Ω_f = Total coefficient of variation associated with the functional form of X

$$= \sqrt{\delta_f^2 + \Delta_f^2}$$

Ω_{Y_n} = Total coefficient of variation associated with Y_n

$$= \sqrt{\delta_{Y_n}^2 + \Delta_{Y_n}^2}$$

ρ_{nm} = Correlation coefficient of Y_n and Y_m, $-1 \leq \rho_{nm} \leq 1$

The subscript "o" denotes that $\delta f / \delta Y_n$ is to be evaluated at the mean values of the variables. Implicit in equations 5-3 and 5-4 are the assumptions that $\Omega Y_n \, 2 << 1$ and nonlinearity in f near the mean values is not large.

b. Survival probability. Consult chapter 9 of TM 5-858-1 for a description of survivability models and chapter 11 therein for a presentation on survivability allocation.

5-3. Types of analytic techniques.

a. In performing verification calculations the outstanding problem stems not from finding a suitable deterministic model, but rather—once having selected a model—from interpreting results probabilistically. There have been attempts to produce compendia of the many analytical techniques that have been applied to calculating the response of systems undergoing nuclear attack (AE WES, 1972). There is almost never an obviously "best" technique to solve a particular problem. The "best" solution depends on understanding all available techniques; the time frame and cost constraints; the accuracy desired, i.e., whether the assessment is preliminary of final; the relative elegance of concomitant analyses; and the state of the art.

b. To be meaningful, verification analyses must be performed probabilistically, i.e., local loads and system responses must be expressed in terms of uncertainties, and system survivability must be expressed as a probability. Uncertainty is defined as the standard deviation of the load and response normalized to the mean. It usually occurs that the the best estimate of the calculated mean response is obtained with the most complete (and usually most expensive) mathematical models. However, the more complicated the models, the more difficult it is to estimate variations in the response due to variations in model parameters.

c. Virtually all analytical methods have been developed to solve differential equations or to represent solutions of those equations. For most real systems, the solution of differential equations is accomplished via numerical techniques, using differencing techniques. Alternatively, the computer is used to numerically evaluate integral solutions or closed-form solutions. Volumes TM 5-858-3 and -4, GE-TEMPO (1974b), and AE WES (1972) reference computer programs pertaining to various weapon effects as well as descriptions of the phenomenology computer codes that calculate the free-field loadings, which the verification analyst may find useful.

d. It is important that the verification analyst recognize that using more sophisticated computational tools is equivalent to the reduction of (or the attempt to reduce) systematic uncertainties. In other words, these techniques are designed to minimize bias in the results. This reduces the ignorance factor and the uncertainties. An obvious consequence is the saving of dollars spent avoiding facility overdesign that otherwise would occur due to use of poor computational tools. The analyst should also recognize that bias and random uncertainty can be reduced by using better data, i.e., more accurate loads and specifications of material properties.

e. Another resource available to the analyst are functional relationships derived from regression equations applied to experimental or computed data in which the response of systems is defined in terms of the important parameters of the system. These solution techniques often are empirical or semi-empirical, and are found in various sources, such as Crawford et al. (1974) and TM 5-585-3. The verification analyst will find most of this information unsuitable for performing deterministic verification analyses; i.e., for calculating the mean response. Nevertheless for the probabilistic analyses discussed subsequently, these techniques may be quite useful.

f. The verification analyst may avail himself o the following techniques for determining the mea response of systems that are subject to nuclea attack:

- —Explicit solutions of differential equations
- —Numerical solutions of differential or integral equations
- —Semi-empirical relationships developed from regression analyses applied to experimental and calculated data

The last technique is most often applied to th design of systems and the first method is usuall too idealized to be much pratical usefulness; th second approach offers the greatest potential t generally address the verification problem.

g. Compared to those methods available for cal culating the mean response of a system, estimatin the expected randomness due to natural variation in material properties and in geometries is grossl more difficult, a task for which little experienc exists and few tools have been developed. Althoug there is awakening of interest in the probabilisti aspects of system response, most of the curren statistical work is too fundamental to be of muc direct application to hardened-facilitie verifications. Therefore, what is lacking in forma computational procedures must be compensated fo with a resourceful application of those analytica tools that are available.

h. The deterministic methods previously outlined genrally involve the solution of differential equations with variable coefficients, whereas deriving the probabilistic response of systems involves the solution of those same equations with both variable and stochastic coefficients. The latter property sharply limits the methods for calculating the response as a random variable. In verification analysis there are, for all practical purposes, only three fundamental techniques for calculating the random response of systems:

- —Monte Carlo methods
- —Engineering judgment
- —Use of simplified uncertainty analyses generally involving sensitivity (changes in response due to changes in system parameters such as stiffness, strength, etc.)

The most versatile and reliable of these techniques is the Monte Carlo method, which can be applied to almost any problem that can be solved deterministically. However, there are certain negative aspects to this technique that should be considered (para 5-4). Due to cost and time constraints or simply because no better alternative seems to exist, the

probabilities of the system response may be simply estimated by applying the judgment of acknowledged experts (para 5-5). On the other hand, if it is possible to explicitly and functionally express the relationship between the input and the response of a system, then direct differentiation of the function may provide a direct means for calculating uncertainties, and subsequently the survival probabilities of the systems (para 5-6).

5-4. The Monte Carlo method.

a. The correspondence between the experimental techniques described elsewhere in this volume and the mathematica approaches that seek to simulate the experimental method is achieved by a procedure called "mathematical experimentation." The form most widely used is called "Monte Carlo" or the Monte Carlo simulation.

b. A simple application of the Monte Carlo process consists of the selection of random variable from an appropriate probability-density distribution that describes the loading function and the geometrical and constitutive parameters of a system, and subsequently calculating the deterministic response for each of the random selections.

c. More complicated applications of the Monte Carlo technique involve multiple systems interrelated to each other. By linking the results of various Monte Carlo solutions together, verification analyses of large complex systems can be performed.

d. Although the Monte Carlo method can be used in many applications, there are disadvantages that must be considered: Cost, loss of visibility, and requirement for statistical input. In order to control costs, the verification analyst may select a sophisticated analytical procedure for computing the mean response of the system (to reduce bias errors), and select an "equivalent" but simpler mathematical model for producing Monte Carlo t solutions (to provide information on the random nature of the response).

e. In linked analyses, in which the results of the Monte Carlo problem are used as input to another Monte Carlo problem, the uncertainties in the final calculation may be governed by errors in the assumed nature of the randomness of the system parameters. To minimize costs it is desirable to reduce the number of Monte Carlo solutions as much as possible, but the use of a crude Monte Carlo mesh introduces further uncertainties. These can be mitigated by increasing the number of solutions, but the improvement in accuracy of the random response is relatively insensitive to this technique.

f. When Monte Carlo calculations are performed, the phenomenological relationship between the random variations in the system parameters and the random nature of the response may be obscured. Auxiliary sensitivity studies using simpler models can help in understanding the parent Monte Carlo calculations.

g. The Monte Carlo method requires that the parameters of the system be defined statistically. These statistical data are obtained experimentally or are estimated. Errors can be reduced by conducting more extensive tests to determine the true nature of the system variables.

h. The verification analyst will want to study the specialized techniques that have been developed for the practical implementation of the Monte Carlo method. One such well-known technique is Rowan (1974).

i. A modified Monte Carlo approach can be adopted in which the partial derivatives in equation 5-4 can be numerically obtained by randomly varying the independent variables Y_n in the vicinity of the mean value to obtain the corresponding variation in the function f. The rpocedure is a formalization of the method discussed in paragraphs 4-2 *e* and *f* of TM 5-858-2, and noted in paragraph 5-6 *c* below.

5-5. Engineering judgment.

a. In many cases, especially during the early phases of hardness verification, it will be judged not feasible to embark on a Monte Carlo approach or to use the approach discussed in paragraph 5-6. It may be necessary to estimate the probabilistic nature of the system response whose mean value was obtained by deterministic computations. Because of his or her familiarity with the solution technique and a grasp of the range of system parameter variations, the analyst will often estimate the distribution of responses around the mean value. This estimate will draw almost exclusively on experience, coupled perhaps with auxiliary calculations that provided insight into the sensitivity of the parametrs in the analysis. When using this method, the analyst should avoid selecting the most adverse condition of each parameter to assess the severest system response. The probability of uniformly encountering the most detrimental extremes of each parameter is very remote and corresponds to a very small probability of

occurrence—much less than the probabilities of each independent parameter selection.

5-6. Direct differentiation of functions.

a. When the solutions to differential equations can be expressed in a functional form, then the uncertainties can be calculated by evaluating the partial derivatives in equation 5-4. For example, the atmospheric transmission of thermal energy is often expressed in the simple equation

$$T = e^{-\sigma R_S}$$

where is a coefficient and R_s is the slant range. The total uncertainty will then be

$$\Omega_T^2 = \Omega_f^2 + \sigma^2 R_s^2 \left(\Omega_\sigma^2 + \Omega_{R_s}^2 \right)$$

where Ω_f is the total uncertainty of the functional form of equation 5-5, and Ω_σ and Ω_{Rs} are the total uncertainties of σ and R_s respectively.

b. As a pratical matter, the simplified relation ships in the response equations may not yield th best prediction of the mean response, since othe important variables may be overlooked or not com pletely represented. Most such simple relationship are probably more useful for estimatin uncertainty than for calculating the mean response It would be more appropriate to calculate the mea response by using one of the more complete deter ministic procedures referenced in paragraph 5-2.

c. For systems that are not grossly nonlinear equation 5-4 may be solved numberically by vary ing the parameters of the system in small incre ments to evaluate the various partial derivatives $\partial f / \partial X_i$. Usually, each independent parameter would be varied at least once above and once below its mean value so that the derivatives could b computed from polynomials fitted to the respons calculations.

CHAPTER 6
VERIFICATION METHODOLOGY

6-1. Introduction.

a. In order to perform a verification analysis, the analyst must define the extent of the system to which the verification procedures will be applied. The "system" to be verified may be a complete facility or a functional unit that forms part of the facility, or a submit, subsystem, or element.

b. Most facilities are so complex that it is neither practical nor desirable to consider independently all elements or even all subsystems or systems in a verification analysis. Usually, many parts of a facility will not be susceptible to every nuclear weapon effect or, occasionally, some parts will not be susceptible to any nuclear weapon effect. Thus, it is necessary to select (based on estimate of design loads and resistances) which parts of the complete facility are susceptible and, of these, which are most prone to failure under a specified attack. Those parts that are neither susceptible nor threatened will not need further analysis. The remaining parts will then be subjected to a verification analysis as subsequently described.

6-2. Diagrams, network logic, fault trees, and Boolean algebra.

a. Procedure. Applying the various techniques described in previous sections of the manual is facilitated by following this procedure:

—Construct functional block diagrams
—Construct network logic or fault-tree diagrams
—Write and simplify Boolean equations
—Determine resistances and compute element uncertainties
—Define loads and uncertainties
—Compute subsystem and system uncertainties and compute survival probabilities where required.

b. Functional block diagram. The functional block diagram is prepared to orient the analyst to the interrelationships between the physical or functional parts of a system. It is most commonly exemplified by schematic diagrams, which are then used to construct logic diagrams.

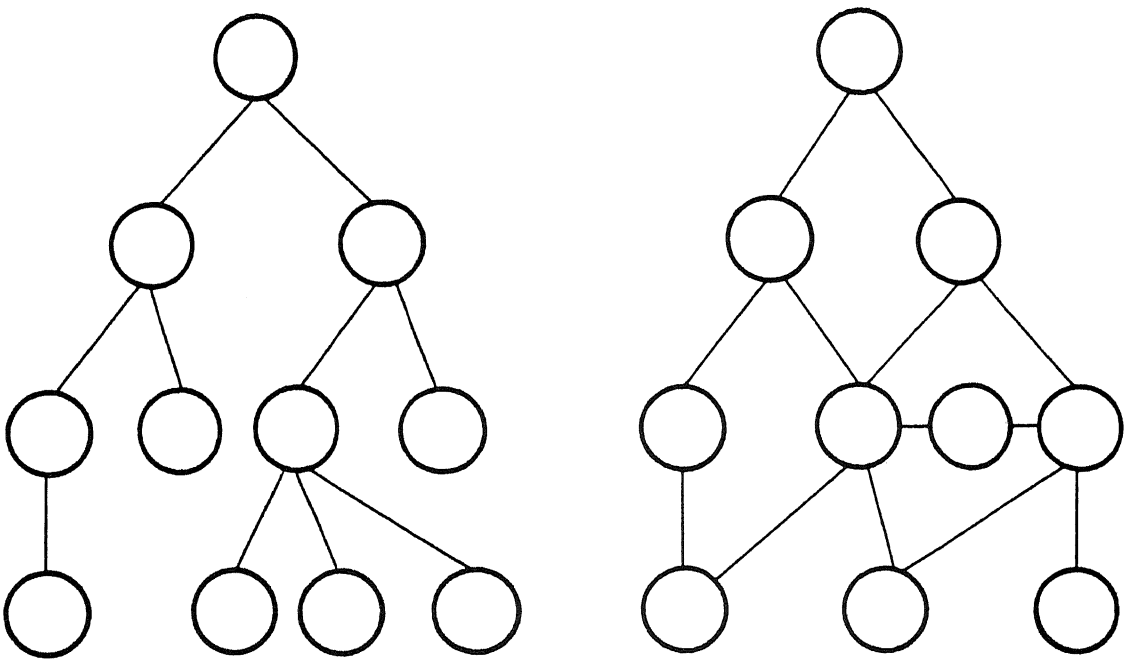
c. Network logic and fault-tree diagrams. Network and tree diagrams, both of which can be useful in hardness-verification programs, are depicted in figure 6-1. However, for complete facilities, systems, subsystems, and even elements, the tree diagram is most often used, since there is usually no complicated logic that would require network diagrams. Only tree analyses are discussed in this volume.

d. Fault tree. An example of a generalized fault tree is shown in figure 6-2. It is diagrammatic representation of the interrelationships between the various failure modes of a system and the environments that potentially could induce failure. Generally, it can be said that a fault tree for a complete facility consists of N systems, each of which has M subsystems, each of which is in turn composed of Q elements. An element will have z functional failure modes, each of which is excited by S loads. In reality, each functional failure mode may have contributory components either in parallel to each other or in series. Also, the fault tree is often expanded to show the resistances that react against the loads. The analyst may construct a tree for any point in the system, ranging from the entire facility to any element within a subsystem. Figure 6-2 is a fault tree for an entire facility.

(1) When all of the elements that are to be included in the fault tree have been identified and diagrammed to show their relationship to each other (this information is obtained from the functional block diagram discussed in b above), then the failure modes for each element should be identified if they bear some positive relationship to the mechanical, radiative, thermal, and other thermonuclear elements. The local environment, i.e., the loads exciting each response leading to a failure mode, should also be identified. The failure modes and loads are then added to the fault tree as shown in figure 6-2. More than one element, subsystem, or system can be considered in the analysis. The larger the physical system involved, the more complete will be the fault tree. However, the tree will also become more complex. Initially, the fault trees are constructed without regard to simplification because their primary purpose is to provide a complete (and perhaps redundant) description of the system, its failure modes, the loads acting on it, and the resistances.

(2) When constructing the fault trees, the overall complexity may be minimized by removing superhard or supersoft systems, subsystems, or elements from consideration; and by beginning at the lowest level of the tree that is practicable, i.e., at the element level. Nevertheless, for a system, subsystem, or element of any real complexity, it is inevitable that the first construction will contain redundancies and interdependencies that would not be immediately obvious. A simplifying procedure is required.

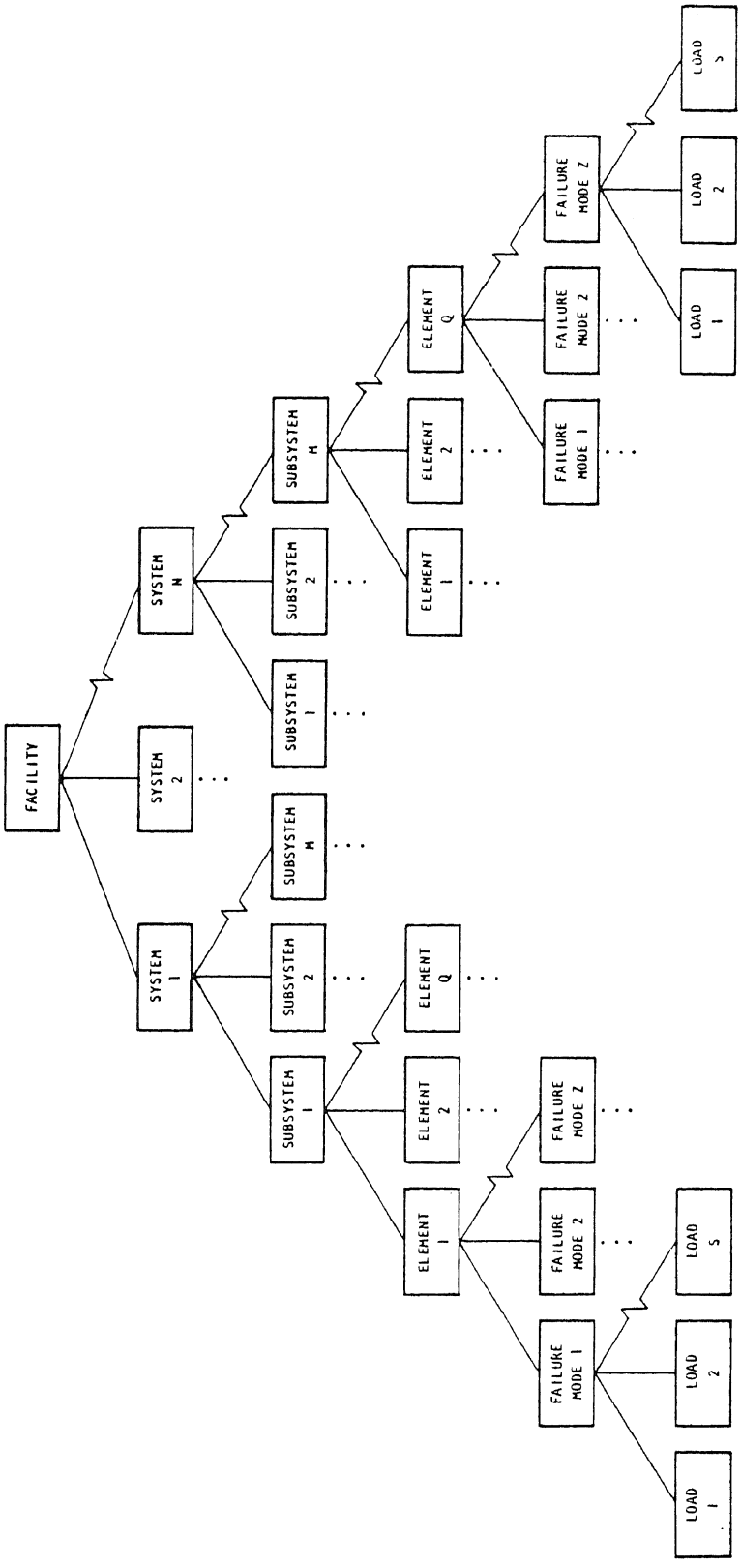
Figure 6-1. Types of logic diagrams.



(a) Tree (b) Network

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Figure 6-2. Typical generalized fault tree.



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e. Boolean equations. Fortunately, the fault tree can be used to develop Boolean equations that will reveal interdependencies and eliminate redundancies. This is accomplished by writing the Boolean equations for the original fault tree and then reducing the equations to their simplest form. A new fault tree can then be constructed from the new Boolean equations, and this revision will be void of redundant information.

(1) In order to implement Boolean algebra, the fault trees are usually presented in the particular form typified in figure 6-3. The symbols are called "gates;" the Boolean logic depends on the type of gate involved. Hammer (1972) describes the specialized fault tree and Boolean algebra. An application to hardened systems is presented by Collins (1975).

(2) An extremely important feature of Boolean algebra is that the equations can be used to designate the survival or failure probability of the system under study. (See Collins, 1975.)

6-3. Elements of verification analysis.

a. Resistance. One of the principal purposes of this volume has been to establish that resistance is a random variable. The character of the load and the resistance are expressed as uncertainty factors that are defined as a measure of scatter (variance) normalized to the mean-squared response. Moreover, uncertainty is generally composed of a random component (a reflection of natural variation) and a systematic component (an expression of ignorance). How these uncertainties can be determined and how survival probabilities can be computed were discussed in paragraph 5-2.

b. Local load environment. The nuclear weapon effects exciting a system usually can be considered random variables, since free-field weapon effect loads are transmitted through the parts of a facility whose transmission characteristics, determined by its geometrical and material properties, are at best only statistically known. Hence, the local environments are probabilistic, and are modifications (amplification or attenuation) of one or more of the free-field, nuclear weapon-effect loads. If only the primary environment is known, than either the local environment must be arbitrarily specified or it must be determined. If it is to be determined, the values must be derived by the use of transfer functions, which relate free-field environments to local-load environments. Because of the nature of the real systems, the transfer functions are also random variables. The relationship among these variables is shown in figure 6-4.

c. Transfer functions. Transfer functions link th primary nuclear weapon-effect loads to the loc loads acting on the system, subsystem, or elemer under study. When performing an actual verifica tion analysis of a system, the general procedure i first to complete verification of critical element then progress to subsystems, systems, and finall the facility, in building-block fashion. In so doin however, defining the loads at the element lev becomes more difficult, since the analyst will n yet have determined how the primary nuclea weapon-effect loads have been modified by the a tual intervening systems and subsystems. Thus, th verification analyst either must utilize the existin design loads or must develop transfer functions.

(1) Whichever method is used depends on th particulars of the problem under investigation. Fo example, if the design-load specification represent the most advanced (best) estimate of the load, th analyst may continue to use this as the load spec fication. However, if the outgoing verification ana yses indicate that the original estimate was i error, a better estimate of the local loads would b required. Later, as progress is made by solving th fault tree equations, the transfer functions can b corroborated by analyses; also new verification a less comprehensive levels can be conducted when ever the ongoing analyses indicate that the trans fer functions were erroneously or incompletel specified.

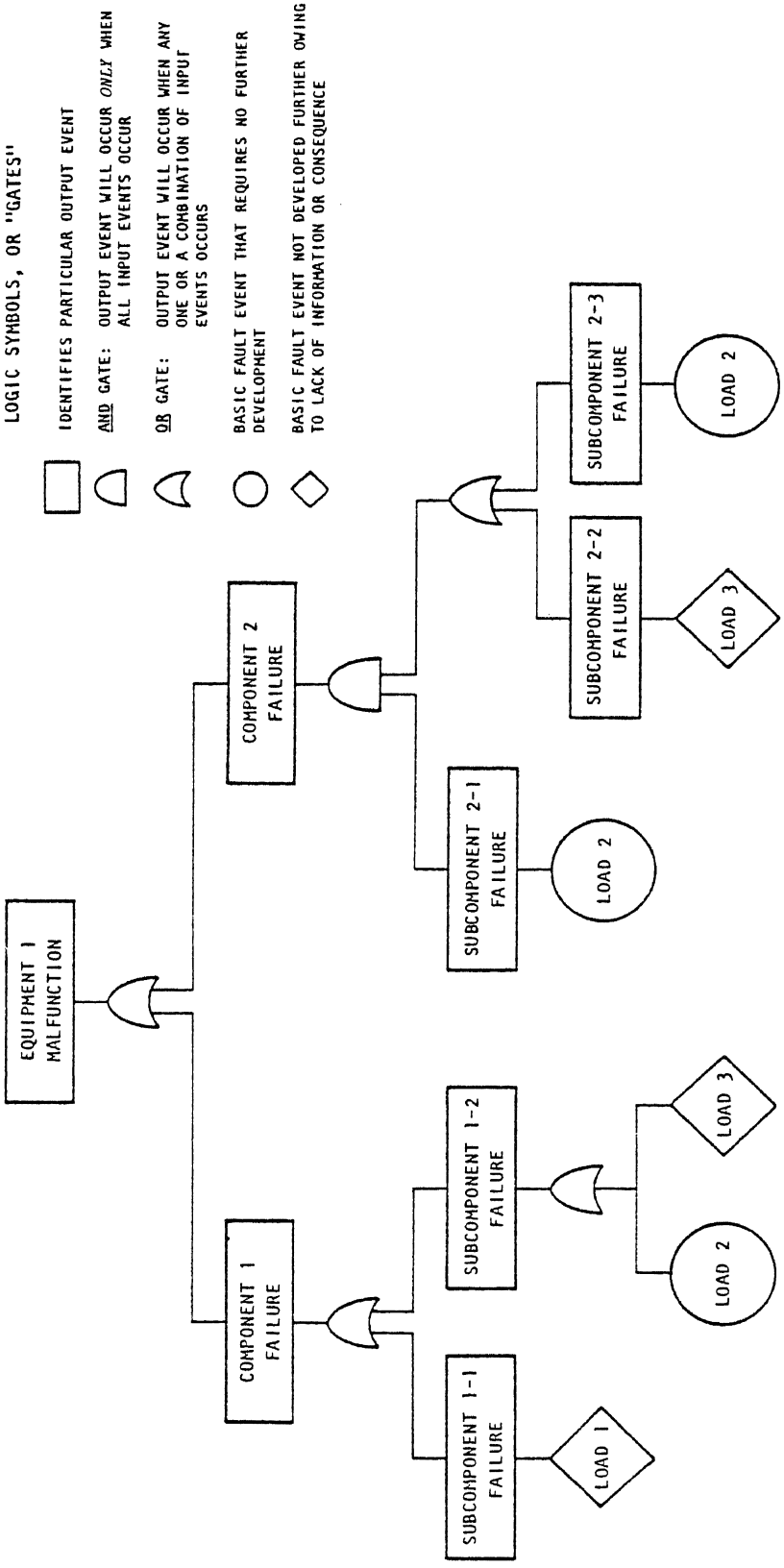
(2) It is again emphasized that transfer func tions have their own uncertainties, consisting o random and systematic components. These uncer tainties add another variation to the local loa environment, beyond the variations (if any are as sumed) existing in the free-field nuclear-weapo effect loads themselves.

6-4. Correlations.

a. An additional factor to be considered is tha local loads acting on a system, subsystem, or ele ment may be transmitted via one or more transfe functions, in series or in parallel, that may b correlated with each other. The simplest configura tion comes from Boolean equations derived fron the fault tree. Note that the Boolean algebra auto matically accounts for serial and parallel connec tions. However, it will not account for the degre of correlation between transfer functions; thes must be calculated separately.

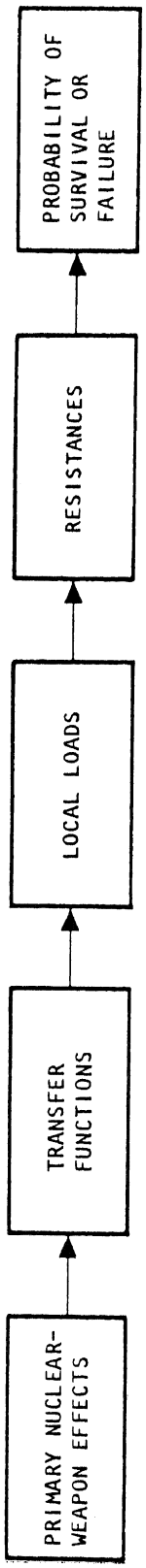
b. A given system may be suceptible to a numbe of nuclear-weapon-effect loads. At the particula point where verification is being performed, ther may be some degree of correlation between loca environments, transfer functions, or resistances

Figure 6-3. Typical Fault Tree with Network Logic Symbols



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Figure 6-4. Loads, Transfer Functions, and Resistance.



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ıe degree of correlation is specified by the cor-
lation coefficient ρ_{ij}. Correlation coefficients vary
the range of $-1<\rho<1$. If strong positive cor-
lation occurs, the system is more likely to survive
ıan if the variables were not correlated at all. On
ıe other hand, if strong negative correlation oc-
ırs, the system is less likely to survive than if the
ıriables were not correlated at all. Therefore, in
'aluating equation 5-9 the correlation coefficients
:tween various elements of the local loads and the
:sistance must be determined.

c. The covariance (which is a more general quan-
ty to be used in equation 5-4) is defined as

$$\rho_{nm}\sigma_{Y_n}\sigma_{Y_m}=\frac{1}{N-1}\sum_{\substack{n=1\\m=1}}^{N}(\hat{y}_n-\overline{y}_n)(\hat{y}_m-\overline{y}_m)$$

here Y_n and Y_m are any two of N variables cor-
:sponding to the resistance function or the load
ınction. The notation $\hat{y}$ indicates selected values of
ıe model representing the random variable Y, and
is the mean of those selected values. The quan-
ty o_y is the standard deviation of the variable Y.
quation 5-7 is evaluated by randomly selecting
alues for the variables $\hat{y}_n$ and $\hat{y}_m$. For example, $\hat{y}_n$
ıay represent random values for the stiffness of
ɔncrete, and $\hat{y}_m$ may represen random values for
ıe damping properties of the same concrete. If the
tiffness and damping are totally uncorrelated (i.e.,
ɔtally independent of each other), the quantity
'ithin the summation of equation 5-7 will tend to
ero as N becomes large and $\rho_{nm}\approx 0$; on the other
and, if the stiffness and damping are negatively
orrelated (i.e., if selections of $\hat{y}_n>\overline{y}_m$ are more
ften than not produce the condition that $\hat{y}_m<\overline{y}_m$,
hen the quantity within the summation will tend
oward a negative number and ρ_{ij} will be a nega-
ive number for large values of N. Coversely, posi-
ive correlation ($\rho_{nm}>0$) would indicate that as the
oncrete stiffness increases, the damping also in-
reases. The limiting conditions for the correlation
oefficient are $-1<\rho_{nm}<1$.

APPENDIX A
BINOMIAL DISTRIBUTION

This appendix contains two tables in support of statistical analysis, Chapter 3. Use Table A-1 in determining the probability of s=r successes in n trials, table A-2 for s≥r successes in n trials.

TABLE A-1. INDIVIDUAL TERMS

PROBABILITY OF REALIZING s = r SUCCESSES IN n TRIALS

$$P(s = r/n, p) = \frac{n!}{r!(n - r)!} p^r q^{n-r}$$

p	n = 2 r = 1	n = 2 r = 0	n = 3 r = 2	n = 3 r = 1	n = 3 r = 0	n = 4 r = 3	p
.01	.0198	.9801	.0003	.0294	.9703	.0000	.01
.02	.0392	.9604	.0012	.0576	.9412	.0000	.02
.03	.0582	.9409	.0026	.0847	.9127	.0001	.03
.04	.0768	.9216	.0046	.1106	.8847	.0002	.04
.05	.0950	.9025	.0071	.1354	.8574	.0005	.05
.06	.1128	.8836	.0102	.1590	.8306	.0008	.06
.07	.1302	.8649	.0137	.1816	.8044	.0013	.07
.08	.1472	.8464	.0177	.2031	.7787	.0019	.08
.09	.1638	.8281	.0221	.2236	.7536	.0027	.09
.10	.1800	.8100	.0270	.2430	.7290	.0036	.10
.11	.1958	.7921	.0323	.2614	.7050	.0047	.11
.12	.2112	.7744	.0380	.2788	.6815	.0061	.12
.13	.2262	.7569	.0441	.2952	.6585	.0076	.13
.14	.2408	.7396	.0506	.3106	.6361	.0094	.14
.15	.2550	.7225	.0574	.3251	.6141	.0115	.15
.16	.2688	.7056	.0645	.3387	.5927	.0138	.16
.17	.2822	.6889	.0720	.3513	.5718	.0163	.17
.18	.2952	.6724	.0797	.3631	.5514	.0191	.18
.19	.3078	.6561	.0877	.3740	.5314	.0222	.19
.20	.3200	.6400	.0960	.3840	.5120	.0256	.20
.21	.3318	.6241	.1045	.3932	.4930	.0293	.21
.22	.3432	.6084	.1133	.4015	.4746	.0332	.22
.23	.3542	.5929	.1222	.4091	.4565	.0375	.23
.24	.3648	.5776	.1313	.4159	.4390	.0420	.24
.25	.3750	.5625	.1406	.4219	.4219	.0469	.25
.26	.3848	.5476	.1501	.4271	.4052	.0520	.26
.27	.3942	.5329	.1597	.4316	.3890	.0575	.27
.28	.4032	.5184	.1693	.4355	.3732	.0632	.28
.29	.4118	.5041	.1791	.4386	.3579	.0693	.29
.30	.4200	.4900	.1890	.4410	.3430	.0756	.30
.31	.4278	.4761	.1989	.4428	.3285	.0822	.31
.32	.4352	.4624	.2089	.4439	.3144	.0891	.32
.33	.4422	.4489	.2189	.4444	.3008	.0963	.33
.34	.4488	.4356	.2289	.4443	.2875	.1038	.34
.35	.4550	.4225	.2389	.4436	.2746	.1115	.35
.36	.4608	.4096	.2488	.4424	.2621	.1194	.36
.37	.4662	.3969	.2587	.4406	.2500	.1276	.37
.38	.4712	.3844	.2686	.4382	.2383	.1361	.38
.39	.4758	.3721	.2783	.4354	.2270	.1447	.39
.40	.4800	.3600	.2880	.4320	.2160	.1536	.40
.41	.4838	.3481	.2975	.4282	.2054	.1627	.41
.42	.4872	.3364	.3069	.4239	.1951	.1719	.42
.43	.4902	.3249	.3162	.4191	.1852	.1813	.43
.44	.4928	.3136	.3252	.4140	.1756	.1908	.44
.45	.4950	.3025	.3341	.4084	.1664	.2005	.45
.46	.4968	.2916	.3428	.4024	.1575	.2102	.46
.47	.4982	.2809	.3512	.3961	.1489	.2201	.47
.48	.4992	.2704	.3594	.3894	.1406	.2300	.48
.49	.4998	.2601	.3674	.3823	.1327	.2400	.49
.50	.5000	.2500	.3750	.3750	.1250	.2500	.50

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TABLE A-1. (CONTINUED)

p	n = 4 r = 2	n = 4 r = 1	n = 4 r = 0	n = 5 r = 4	n = 5 r = 3	n = 5 r = 2	p
.01	.0006	.0388	.9606	.0000	.0000	.0010	.01
.02	.0023	.0753	.9224	.0000	.0001	.0038	.02
.03	.0051	.1095	.8853	.0000	.0003	.0082	.03
.04	.0088	.1416	.8493	.0000	.0006	.0142	.04
.05	.0135	.1715	.8145	.0000	.0011	.0214	.05
.06	.0191	.1993	.7807	.0001	.0019	.0299	.06
.07	.0254	.2252	.7481	.0001	.0030	.0394	.07
.08	.0325	.2492	.7164	.0002	.0043	.0498	.08
.09	.0402	.2713	.6857	.0003	.0060	.0610	.09
.10	.0486	.2916	.6561	.0004	.0081	.0729	.10
.11	.0575	.3102	.6274	.0007	.0105	.0853	.11
.12	.0669	.3271	.5997	.0009	.0134	.0981	.12
.13	.0767	.3424	.5729	.0012	.0166	.1113	.13
.14	.0870	.3562	.5470	.0017	.0203	.1247	.14
.15	.0975	.3685	.5220	.0022	.0244	.1382	.15
.16	.1084	.3793	.4979	.0028	.0289	.1517	.16
.17	.1195	.3888	.4746	.0035	.0338	.1652	.17
.18	.1307	.3970	.4521	.0043	.0392	.1786	.18
.19	.1421	.4039	.4305	.0053	.0450	.1919	.19
.20	.1536	.4096	.4096	.0064	.0512	.2048	.20
.21	.1651	.4142	.3895	.0077	.0578	.2174	.21
.22	.1767	.4176	.3702	.0091	.0648	.2297	.22
.23	.1882	.4200	.3515	.0108	.0721	.2415	.23
.24	.1996	.4214	.3336	.0126	.0798	.2529	.24
.25	.2109	.4219	.3164	.0146	.0879	.2637	.25
.26	.2221	.4214	.2999	.0169	.0962	.2739	.26
.27	.2331	.4201	.2840	.0194	.1049	.2836	.27
.28	.2439	.4180	.2687	.0221	.1138	.2926	.28
.29	.2544	.4152	.2541	.0251	.1229	.3010	.29
.30	.2646	.4116	.2401	.0283	.1323	.3087	.30
.31	.2745	.4074	.2267	.0319	.1418	.3157	.31
.32	.2841	.4025	.2138	.0357	.1515	.3220	.32
.33	.2933	.3970	.2015	.0397	.1613	.3275	.33
.34	.3021	.3910	.1897	.0441	.1712	.3323	.34
.35	.3105	.3845	.1785	.0488	.1811	.3364	.35
.36	.3185	.3775	.1678	.0537	.1911	.3397	.36
.37	.3260	.3701	.1575	.0590	.2010	.3423	.37
.38	.3330	.3623	.1478	.0646	.2109	.3441	.38
.39	.3396	.3541	.1385	.0706	.2207	.3452	.39
.40	.3456	.3456	.1296	.0768	.2304	.3456	.40
.41	.3511	.3368	.1212	.0834	.2399	.3452	.41
.42	.3560	.3278	.1132	.0902	.2492	.3442	.42
.43	.3604	.3185	.1056	.0974	.2583	.3424	.43
.44	.3643	.3091	.0983	.1049	.2671	.3400	.44
.45	.3675	.2995	.0915	.1128	.2757	.3369	.45
.46	.3702	.2897	.0850	.1209	.2838	.3332	.46
.47	.3723	.2799	.0789	.1293	.2916	.3289	.47
.48	.3738	.2700	.0731	.1380	.2990	.3240	.48
.49	.3747	.2600	.0677	.1470	.3060	.3185	.49
.50	.3750	.2500	.0625	.1562	.3125	.3125	.50

TABLE A-1. INDIVIDUAL TERMS

PROBABILITY OF REALIZING s = r SUCCESSES IN n TRIALS

$$P(s = r/n, p) = \frac{n!}{r!(n - r)!} p^r q^{n-r}$$

p	n = 2 r = 1	n = 2 r = 0	n = 3 r = 2	n = 3 r = 1	n = 3 r = 0	n = 4 r = 3	p
.01	.0198	.9801	.0003	.0294	.9703	.0000	.01
.02	.0392	.9604	.0012	.0576	.9412	.0000	.02
.03	.0582	.9409	.0026	.0847	.9127	.0001	.03
.04	.0768	.9216	.0046	.1106	.8847	.0002	.04
.05	.0950	.9025	.0071	.1354	.8574	.0005	.05
.06	.1128	.8836	.0102	.1590	.8306	.0008	.06
.07	.1302	.8649	.0137	.1816	.8044	.0013	.07
.08	.1472	.8464	.0177	.2031	.7787	.0019	.08
.09	.1638	.8281	.0221	.2236	.7536	.0027	.09
.10	.1800	.8100	.0270	.2430	.7290	.0036	.10
.11	.1958	.7921	.0323	.2614	.7050	.0047	.11
.12	.2112	.7744	.0380	.2788	.6815	.0061	.12
.13	.2262	.7569	.0441	.2952	.6585	.0076	.13
.14	.2408	.7396	.0506	.3106	.6361	.0094	.14
.15	.2550	.7225	.0574	.3251	.6141	.0115	.15
.16	.2688	.7056	.0645	.3387	.5927	.0138	.16
.17	.2822	.6889	.0720	.3513	.5718	.0163	.17
.18	.2952	.6724	.0797	.3631	.5514	.0191	.18
.19	.3078	.6561	.0877	.3740	.5314	.0222	.19
.20	.3200	.6400	.0960	.3840	.5120	.0256	.20
.21	.3318	.6241	.1045	.3932	.4930	.0293	.21
.22	.3432	.6084	.1133	.4015	.4746	.0332	.22
.23	.3542	.5929	.1222	.4091	.4565	.0375	.23
.24	.3648	.5776	.1313	.4159	.4390	.0420	.24
.25	.3750	.5625	.1406	.4219	.4219	.0469	.25
.26	.3848	.5476	.1501	.4271	.4052	.0520	.26
.27	.3942	.5329	.1597	.4316	.3890	.0575	.27
.28	.4032	.5184	.1693	.4355	.3732	.0632	.28
.29	.4118	.5041	.1791	.4386	.3579	.0693	.29
.30	.4200	.4900	.1890	.4410	.3430	.0756	.30
.31	.4278	.4761	.1989	.4428	.3285	.0822	.31
.32	.4352	.4624	.2089	.4439	.3144	.0891	.32
.33	.4422	.4489	.2189	.4444	.3008	.0963	.33
.34	.4488	.4356	.2289	.4443	.2875	.1038	.34
.35	.4550	.4225	.2389	.4436	.2746	.1115	.35
.36	.4608	.4096	.2488	.4424	.2621	.1194	.36
.37	.4662	.3969	.2587	.4406	.2500	.1276	.37
.38	.4712	.3844	.2686	.4382	.2383	.1361	.38
.39	.4758	.3721	.2783	.4354	.2270	.1447	.39
.40	.4800	.3600	.2880	.4320	.2160	.1536	.40
.41	.4838	.3481	.2975	.4282	.2054	.1627	.41
.42	.4872	.3364	.3069	.4239	.1951	.1719	.42
.43	.4902	.3249	.3162	.4191	.1852	.1813	.43
.44	.4928	.3136	.3252	.4140	.1756	.1908	.44
.45	.4950	.3025	.3341	.4084	.1664	.2005	.45
.46	.4968	.2916	.3428	.4024	.1575	.2102	.46
.47	.4982	.2809	.3512	.3961	.1489	.2201	.47
.48	.4992	.2704	.3594	.3894	.1406	.2300	.48
.49	.4998	.2601	.3674	.3823	.1327	.2400	.49
.50	.5000	.2500	.3750	.3750	.1250	.2500	.50

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TABLE A-1. (CONTINUED)

p	n = 4 r = 2	n = 4 r = 1	n = 4 r = 0	n = 5 r = 4	n = 5 r = 3	n = 5 r = 2	p
.01	.0006	.0388	.9606	.0000	.0000	.0010	.01
.02	.0023	.0753	.9224	.0000	.0001	.0038	.02
.03	.0051	.1095	.8853	.0000	.0003	.0082	.03
.04	.0088	.1416	.8493	.0000	.0006	.0142	.04
.05	.0135	.1715	.8145	.0000	.0011	.0214	.05
.06	.0191	.1993	.7807	.0001	.0019	.0299	.06
.07	.0254	.2252	.7481	.0001	.0030	.0394	.07
.08	.0325	.2492	.7164	.0002	.0043	.0498	.08
.09	.0402	.2713	.6857	.0003	.0060	.0610	.09
.10	.0486	.2916	.6561	.0004	.0081	.0729	.10
.11	.0575	.3102	.6274	.0007	.0105	.0853	.11
.12	.0669	.3271	.5997	.0009	.0134	.0981	.12
.13	.0767	.3424	.5729	.0012	.0166	.1113	.13
.14	.0870	.3562	.5470	.0017	.0203	.1247	.14
.15	.0975	.3685	.5220	.0022	.0244	.1382	.15
.16	.1084	.3793	.4979	.0028	.0289	.1517	.16
.17	.1195	.3888	.4746	.0035	.0338	.1652	.17
.18	.1307	.3970	.4521	.0043	.0392	.1786	.18
.19	.1421	.4039	.4305	.0053	.0450	.1919	.19
.20	.1536	.4096	.4096	.0064	.0512	.2048	.20
.21	.1651	.4142	.3895	.0077	.0578	.2174	.21
.22	.1767	.4176	.3702	.0091	.0648	.2297	.22
.23	.1882	.4200	.3515	.0108	.0721	.2415	.23
.24	.1996	.4214	.3336	.0126	.0798	.2529	.24
.25	.2109	.4219	.3164	.0146	.0879	.2637	.25
.26	.2221	.4214	.2999	.0169	.0962	.2739	.26
.27	.2331	.4201	.2840	.0194	.1049	.2836	.27
.28	.2439	.4180	.2687	.0221	.1138	.2926	.28
.29	.2544	.4152	.2541	.0251	.1229	.3010	.29
.30	.2646	.4116	.2401	.0283	.1323	.3087	.30
.31	.2745	.4074	.2267	.0319	.1418	.3157	.31
.32	.2841	.4025	.2138	.0357	.1515	.3220	.32
.33	.2933	.3970	.2015	.0397	.1613	.3275	.33
.34	.3021	.3910	.1897	.0441	.1712	.3323	.34
.35	.3105	.3845	.1785	.0488	.1811	.3364	.35
.36	.3185	.3775	.1678	.0537	.1911	.3397	.36
.37	.3260	.3701	.1575	.0590	.2010	.3423	.37
.38	.3330	.3623	.1478	.0646	.2109	.3441	.38
.39	.3396	.3541	.1385	.0706	.2207	.3452	.39
.40	.3456	.3456	.1296	.0768	.2304	.3456	.40
.41	.3511	.3368	.1212	.0834	.2399	.3452	.41
.42	.3560	.3278	.1132	.0902	.2492	.3442	.42
.43	.3604	.3185	.1056	.0974	.2583	.3424	.43
.44	.3643	.3091	.0983	.1049	.2671	.3400	.44
.45	.3675	.2995	.0915	.1128	.2757	.3369	.45
.46	.3702	.2897	.0850	.1209	.2838	.3332	.46
.47	.3723	.2799	.0789	.1293	.2916	.3289	.47
.48	.3738	.2700	.0731	.1380	.2990	.3240	.48
.49	.3747	.2600	.0677	.1470	.3060	.3185	.49
.50	.3750	.2500	.0625	.1562	.3125	.3125	.50

TABLE A-1. (CONTINUED)

p	n = 5 r = 1	n = 5 r = 0	n = 6 r = 5	n = 6 r = 4	n = 6 r = 3	n = 6 r = 2	p
.01	.0480	.9510	.0000	.0000	.0000	.0014	.01
.02	.0922	.9039	.0000	.0000	.0002	.0055	.02
.03	.1328	.8587	.0000	.0000	.0005	.0120	.03
.04	.1699	.8154	.0000	.0000	.0011	.0204	.04
.05	.2036	.7738	.0000	.0001	.0021	.0305	.05
.06	.2342	.7339	.0000	.0002	.0036	.0422	.06
.07	.2618	.6957	.0000	.0003	.0055	.0550	.07
.08	.2866	.6591	.0000	.0005	.0080	.0688	.08
.09	.3086	.6240	.0000	.0008	.0110	.0833	.09
.10	.3281	.5905	.0001	.0012	.0146	.0984	.10
.11	.3451	.5584	.0001	.0017	.0188	.1139	.11
.12	.3598	.5277	.0001	.0024	.0236	.1295	.12
.13	.3724	.4984	.0002	.0032	.0289	.1452	.13
.14	.3829	.4704	.0003	.0043	.0349	.1608	.14
.15	.3915	.4437	.0004	.0055	.0415	.1762	.15
.16	.3983	.4182	.0005	.0069	.0486	.1912	.16
.17	.4034	.3939	.0007	.0086	.0562	.2057	.17
.18	.4069	.3707	.0009	.0106	.0643	.2197	.18
.19	.4089	.3487	.0012	.0128	.0729	.2331	.19
.20	.4096	.3277	.0015	.0154	.0819	.2458	.20
.21	.4090	.3077	.0019	.0182	.0913	.2577	.21
.22	.4072	.2887	.0024	.0214	.1011	.2687	.22
.23	.4043	.2707	.0030	.0249	.1111	.2789	.23
.24	.4003	.2536	.0036	.0287	.1214	.2882	.24
.25	.3955	.2373	.0044	.0330	.1318	.2966	.25
.26	.3898	.2219	.0053	.0375	.1424	.3041	.26
.27	.3834	.2073	.0063	.0425	.1531	.3105	.27
.28	.3762	.1935	.0074	.0478	.1639	.3160	.28
.29	.3685	.1804	.0087	.0535	.1746	.3206	.29
.30	.3602	.1681	.0102	.0595	.1852	.3241	.30
.31	.3513	.1564	.0119	.0660	.1957	.3267	.31
.32	.3421	.1454	.0137	.0727	.2061	.3284	.32
.33	.3325	.1350	.0157	.0799	.2162	.3292	.33
.34	.3226	.1252	.0180	.0873	.2260	.3290	.34
.35	.3124	.1160	.0205	.0951	.2355	.3280	.35
.36	.3020	.1074	.0232	.1032	.2446	.3261	.36
.37	.2914	.0992	.0262	.1116	.2533	.3235	.37
.38	.2808	.0916	.0295	.1202	.2616	.3201	.38
.39	.2700	.0845	.0330	.1291	.2693	.3159	.39
.40	.2592	.0778	.0369	.1382	.2765	.3110	.40
.41	.2484	.0715	.0410	.1475	.2831	.3055	.41
.42	.2376	.0656	.0455	.1570	.2891	.2994	.42
.43	.2270	.0602	.0503	.1666	.2945	.2928	.43
.44	.2164	.0551	.0554	.1763	.2992	.2856	.44
.45	.2059	.0503	.0609	.1861	.3032	.2780	.45
.46	.1956	.0459	.0667	.1958	.3065	.2699	.46
.47	.1854	.0418	.0729	.2056	.3091	.2615	.47
.48	.1755	.0380	.0795	.2153	.3110	.2527	.48
.49	.1657	.0345	.0864	.2249	.3121	.2436	.49
.50	.1563	.0313	.0937	.2344	.3125	.2344	.50

TABLE A-1. (CONTINUED)

p	n = 6 r = 1	n = 6 r = 0	n = 7 r = 6	n = 7 r = 5	n = 7 r = 4	n = 7 r = 3	p
.01	.0571	.9415	.0000	.0000	.0000	.0000	.01
.02	.1085	.8858	.0000	.0000	.0000	.0003	.02
.03	.1546	.8330	.0000	.0000	.0000	.0008	.03
.04	.1957	.7828	.0000	.0000	.0001	.0019	.04
.05	.2321	.7351	.0000	.0000	.0002	.0036	.05
.06	.2642	.6899	.0000	.0000	.0004	.0059	.06
.07	.2922	.6470	.0000	.0000	.0007	.0090	.07
.08	.3164	.6064	.0000	.0001	.0011	.0128	.08
.09	.3370	.5679	.0000	.0001	.0017	.0175	.09
.10	.3543	.5314	.0000	.0002	.0026	.0230	.10
.11	.3685	.4970	.0000	.0003	.0036	.0292	.11
.12	.3800	.4644	.0000	.0004	.0049	.0363	.12
.13	.3888	.4336	.0000	.0006	.0066	.0441	.13
.14	.3952	.4046	.0000	.0008	.0086	.0525	.14
.15	.3993	.3771	.0001	.0012	.0109	.0617	.15
.16	.4015	.3513	.0001	.0016	.0136	.0714	.16
.17	.4018	.3269	.0001	.0021	.0167	.0816	.17
.18	.4004	.3040	.0002	.0027	.0203	.0923	.18
.19	.3975	.2824	.0003	.0034	.0242	.1033	.19
.20	.3932	.2621	.0004	.0043	.0287	.1147	.20
.21	.3877	.2431	.0005	.0054	.0336	.1263	.21
.22	.3811	.2252	.0006	.0066	.0389	.1379	.22
.23	.3735	.2084	.0008	.0080	.0447	.1497	.23
.24	.3651	.1927	.0010	.0097	.0510	.1614	.24
.25	.3560	.1780	.0013	.0115	.0577	.1730	.25
.26	.3462	.1642	.0016	.0137	.0648	.1845	.26
.27	.3358	.1513	.0020	.0161	.0724	.1956	.27
.28	.3251	.1393	.0024	.0187	.0803	.2065	.28
.29	.3139	.1281	.0030	.0217	.0886	.2169	.29
.30	.3025	.1176	.0036	.0250	.0972	.2269	.30
.31	.2909	.1079	.0043	.0286	.1062	.2363	.31
.32	.2792	.0989	.0051	.0326	.1154	.2452	.32
.33	.2673	.0905	.0061	.0369	.1248	.2535	.33
.34	.2555	.0827	.0071	.0416	.1345	.2610	.34
.35	.2437	.0754	.0084	.0466	.1442	.2679	.35
.36	.2319	.0687	.0098	.0520	.1541	.2740	.36
.37	.2203	.0625	.0113	.0578	.1640	.2793	.37
.38	.2089	.0568	.0131	.0640	.1739	.2838	.38
.39	.1976	.0515	.0150	.0705	.1838	.2875	.39
.40	.1866	.0467	.0172	.0774	.1935	.2903	.40
.41	.1759	.0422	.0196	.0847	.2031	.2923	.41
.42	.1654	.0381	.0223	.0923	.2125	.2934	.42
.43	.1552	.0343	.0252	.1003	.2216	.2937	.43
.44	.1454	.0308	.0284	.1086	.2304	.2932	.44
.45	.1359	.0277	.0320	.1172	.2388	.2918	.45
.46	.1267	.0248	.0358	.1261	.2468	.2897	.46
.47	.1179	.0222	.0400	.1353	.2543	.2867	.47
.48	.1095	.0198	.0445	.1447	.2612	830	.48
.49	.1014	.0176	.0494	.1543	.2676	.2786	.49
.50	.0938	.0156	.0547	.1641	.2734	.2734	.50

TABLE A-1. (CONTINUED)

p	n = 7 r = 2	n = 7 r = 1	n = 7 r = 0	n = 8 r = 7	n = 8 r = 6	n = 8 r = 5	p
.01	.0020	.0659	.9321	.0000	.0000	.0000	.01
.02	.0076	.1240	.8681	.0000	.0000	.0000	.02
.03	.0162	.1749	.8080	.0000	.0000	.0000	.03
.04	.0274	.2192	.7514	.0000	.0000	.0000	.04
.05	.0406	.2573	.6983	.0000	.0000	.0000	.05
.06	.0555	.2897	.6485	.0000	.0000	.0000	.06
.07	.0716	.3170	.6017	.0000	.0000	.0001	.07
.08	.0886	.3396	.5578	.0000	.0000	.0001	.08
.09	.1061	.3578	.5168	.0000	.0000	.0002	.09
.10	.1240	.3720	.4783	.0000	.0000	.0004	.10
.11	.1419	.3827	.4423	.0000	.0000	.0006	.11
.12	.1596	.3901	.4087	.0000	.0001	.0009	.12
.13	.1769	.3946	.3773	.0000	.0001	.0014	.13
.14	.1936	.3965	.3479	.0000	.0002	.0019	.14
.15	.2097	.3960	.3206	.0000	.0002	.0026	.15
.16	.2248	.3935	.2951	.0000	.0003	.0035	.16
.17	.2391	.3891	.2714	.0000	.0005	.0045	.17
.18	.2523	.3830	.2493	.0000	.0006	.0058	.18
.19	.2643	.3756	.2288	.0001	.0009	.0074	.19
.20	.2753	.3670	.2097	.0001	.0011	.0092	.20
.21	.2850	.3573	.1920	.0001	.0015	.0113	.21
.22	.2935	.3468	.1757	.0002	.0019	.0137	.22
.23	.3007	.3356	.1605	.0002	.0025	.0165	.23
.24	.3067	.3237	.1465	.0003	.0031	.0196	.24
.25	.3115	.3115	.1335	.0004	.0038	.0231	.25
.26	.3150	.2989	.1215	.0005	.0047	.0270	.26
.27	.3174	.2860	.1105	.0006	.0058	.0313	.27
.28	.3186	.2731	.1003	.0008	.0070	.0360	.28
.29	.3186	.2600	.0910	.0010	.0084	.0411	.29
.30	.3177	.2471	.0824	.0012	.0100	.0467	.30
.31	.3156	.2342	.0745	.0015	.0118	.0527	.31
.32	.3127	.2215	.0672	.0019	.0139	.0591	.32
.33	.3088	.2090	.0606	.0023	.0162	.0659	.33
.34	.3040	.1967	.0546	.0028	.0188	.0732	.34
.35	.2985	.1848	.0490	.0033	.0217	.0808	.35
.36	.2922	.1732	.0440	.0040	.0250	.0888	.36
.37	.2853	.1619	.0394	.0048	.0285	.0971	.37
.38	.2778	.1511	.0352	.0057	.0324	.1058	.38
.39	.2698	.1407	.0314	.0067	.0367	.1147	.39
.40	.2613	.1306	.0280	.0079	.0413	.1239	.40
.41	.2524	.1211	.0249	.0092	.0463	.1332	.41
.42	.2431	.1119	.0221	.0107	.0517	.1428	.42
.43	.2336	.1032	.0195	.0124	.0575	.1525	.43
.44	.2239	.0950	.0173	.0143	.0637	.1622	.44
.45	.2140	.0872	.0152	.0164	.0703	.1719	.45
.46	.2040	.0798	.0134	.0188	.0774	.1816	.46
.47	.1940	.0729	.0117	.0215	.0848	.1912	.47
.48	.1840	.0664	.0103	.0244	.0926	.2006	.48
.49	.1740	.0604	.0090	.0277	.1008	.2098	.49
.50	.1641	.0547	.0078	.0312	.1094	.2187	.50

TABLE A-1. (CONTINUED)

p	n = 8 r = 4	n = 8 r = 3	n = 8 r = 2	n = 8 r = 1	n = 8 r = 0	n = 9 r = 8	p
.01	.0000	.0001	.0026	.0746	.9227	.0000	.01
.02	.0000	.0004	.0099	.1389	.8508	.0000	.02
.03	.0001	.0013	.0210	.1939	.7837	.0000	.03
.04	.0002	.0029	.0351	.2405	.7214	.0000	.04
.05	.0004	.0054	.0515	.2793	.6634	.0000	.05
.06	.0007	.0089	.0695	.3113	.6096	.0000	.06
.07	.0013	.0134	.0888	.3370	.5596	.0000	.07
.08	.0021	.0189	.1087	.3570	.5132	.0000	.08
.09	.0031	.0255	.1288	.3721	.4703	.0000	.09
.10	.0046	.0331	.1488	.3826	.4305	.0000	.10
.11	.0064	.0416	.1684	.3892	.3937	.0000	.11
.12	.0087	.0511	.1872	.3923	.3596	.0000	.12
.13	.0115	.0613	.2052	.3923	.3282	.0000	.13
.14	.0147	.0723	.2220	.3897	.2992	.0000	.14
.15	.0185	.0839	.2376	.3847	.2725	.0000	.15
.16	.0228	.0959	.2518	.3777	.2479	.0000	.16
.17	.0277	.1084	.2646	.3691	.2252	.0000	.17
.18	.0332	.1211	.2758	.3590	.2044	.0000	.18
.19	.0393	.1339	.2855	.3477	.1853	.0000	.19
.20	.0459	.1468	.2936	.3355	.1678	.0000	.20
.21	.0530	.1596	.3002	.3226	.1517	.0000	.21
.22	.0607	.1722	.3052	.3092	.1370	.0000	.22
.23	.0689	.1844	.3087	.2953	.1236	.0001	.23
.24	.0775	.1963	.3108	.2812	.1113	.0001	.24
.25	.0865	.2076	.3115	.2670	.1001	.0001	.25
.26	.0959	.2184	.3108	.2527	.0899	.0001	.26
.27	.1056	.2285	.3089	.2386	.0806	.0002	.27
.28	.1156	.2379	.3058	.2247	.0722	.0002	.28
.29	.1258	.2464	.3017	.2110	.0646	.0003	.29
.30	.1361	.2541	.2965	.1977	.0576	.0004	.30
.31	.1465	.2609	.2904	.1847	.0514	.0005	.31
.32	.1569	.2668	.2835	.1721	.0457	.0007	.32
.33	.1673	.2717	.2758	.1600	.0406	.0008	.33
.34	.1775	.2756	.2675	.1484	.0360	.0011	.34
.35	.1875	.2786	.2587	.1373	.0319	.0013	.35
.36	.1973	.2805	.2494	.1267	.0281	.0016	.36
.37	.2067	.2815	.2397	.1166	.0248	.0020	.37
.38	.2157	.2815	.2297	.1071	.0218	.0024	.38
.39	.2242	.2806	.2194	.0981	.0192	.0029	.39
.40	.2322	.2787	.2090	.0896	.0168	.0035	.40
.41	.2397	.2759	.1985	.0816	.0147	.0042	.41
.42	.2465	.2723	.1880	.0742	.0128	.0051	.42
.43	.2526	.2679	.1776	.0672	.0111	.0060	.43
.44	.2580	.2627	.1672	.0608	.0097	.0071	.44
.45	.2627	.2568	.1569	.0548	.0084	.0083	.45
.46	.2665	.2503	.1469	.0493	.0072	.0097	.46
.47	.2695	.2431	.1371	.0442	.0062	.0114	.47
.48	.2717	.2355	.1275	.0395	.0053	.0132	.48
.49	.2730	.2273	.1183	.0352	.0046	.0153	.49
.50	.2734	.2188	.1094	.0313	.0039	.0176	.50

TABLE A-1. (CONTINUED)

p	n = 9 r = 7	n = 9 r = 6	n = 9 r = 5	n = 9 r = 4	n = 9 r = 3	n = 9 r = 2	p
.01	.0000	.0000	.0000	.0000	.0001	.0034	.01
.02	.0000	.0000	.0000	.0000	.0006	.0125	.02
.03	.0000	.0000	.0000	.0001	.0019	.0262	.03
.04	.0000	.0000	.0000	.0003	.0042	.0433	.04
.05	.0000	.0000	.0000	.0006	.0077	.0629	.05
.06	.0000	.0000	.0001	.0012	.0125	.0840	.06
.07	.0000	.0000	.0002	.0021	.0186	.1061	.07
.08	.0000	.0000	.0003	.0034	.0261	.1285	.08
.09	.0000	.0000	.0005	.0052	.0348	.1507	.09
.10	.0000	.0001	.0008	.0074	.0446	.1722	.10
.11	.0000	.0001	.0013	.0103	.0556	.1927	.11
.12	.0000	.0002	.0019	.0138	.0674	.2119	.12
.13	.0000	.0003	.0027	.0179	.0800	.2295	.13
.14	.0000	.0004	.0037	.0228	.0933	.2455	.14
.15	.0000	.0006	.0050	.0283	.1069	.2597	.15
.16	.0001	.0008	.0066	.0345	.1209	.2720	.16
.17	.0001	.0012	.0085	.0415	.1349	.2823	.17
.18	.0001	.0016	.0108	.0490	.1489	.2908	.18
.19	.0002	.0021	.0134	.0573	.1627	.2973	.19
.20	.0003	.0028	.0165	.0661	.1762	.3020	.20
.21	.0004	.0036	.0200	.0754	.1891	.3049	.21
.22	.0005	.0045	.0240	.0852	.2014	.3061	.22
.23	.0007	.0057	.0285	.0954	.2130	.3056	.23
.24	.0010	.0070	.0335	.1060	.2238	.3037	.24
.25	.0012	.0087	.0389	.1168	.2336	.3003	.25
.26	.0016	.0105	.0449	.1278	.2424	.2957	.26
.27	.0020	.0127	.0513	.1388	.2502	.2899	.27
.28	.0025	.0151	.0583	.1499	.2569	.2831	.28
.29	.0031	.0179	.0657	.1608	.2624	.2754	.29
.30	.0039	.0210	.0735	.1715	.2668	.2668	.30
.31	.0047	.0245	.0818	.1820	.2701	.2576	.31
.32	.0057	.0284	.0904	.1921	.2721	.2478	.32
.33	.0069	.0326	.0994	.2017	.2731	.2376	.33
.34	.0082	.0373	.1086	.2109	.2729	.2270	.34
.35	.0098	.0424	.1181	.2194	.2716	.2162	.35
.36	.0116	.0479	.1278	.2272	.2693	.2052	.36
.37	.0136	.0539	.1376	.2344	.2660	.1941	.37
.38	.0158	.0603	.1475	.2407	.2618	.1831	.38
.39	.0184	.0671	.1574	.2462	.2567	.1721	.39
.40	.0212	.0743	.1672	.2508	.2508	.1612	.40
.41	.0244	.0819	.1769	.2545	.2442	.1506	.41
.42	.0279	.0900	.1863	.2573	.2369	.1402	.42
.43	.0318	.0983	.1955	.2592	.2291	.1301	.43
.44	.0360	.1070	.2044	.2601	.2207	.1204	.44
.45	.0407	.1160	.2128	.2600	.2119	.1110	.45
.46	.0458	.1253	.2207	.2590	.2027	.1020	.46
.47	.0512	.1348	.2280	.2571	.1933	.0934	.47
.48	.0571	.1445	.2347	.2543	.1837	.0853	.48
.49	.0635	.1542	.2408	.2506	.1739	.0776	.49
.50	.0703	.1641	.2461	.2461	.1641	.0703	.50

TABLE A-1. (CONTINUED)

p	n = 9 r = 1	n = 9 r = 0	n = 10 r = 9	n = 10 r = 8	n = 10 r = 7	n = 10 r = 6	p
.01	.0830	.9135	.0000	.0000	.0000	.0000	.01
.02	.1531	.8337	.0000	.0000	.0000	.0000	.02
.03	.2116	.7602	.0000	.0000	.0000	.0000	.03
.04	.2597	.6925	.0000	.0000	.0000	.0000	.04
.05	.2985	.6302	.0000	.0000	.0000	.0000	.05
.06	.3292	.5730	.0000	.0000	.0000	.0000	.06
.07	.3525	.5204	.0000	.0000	.0000	.0000	.07
.08	.3695	.4722	.0000	.0000	.0000	.0000	.08
.09	.3809	.4279	.0000	.0000	.0000	.0001	.09
.10	.3874	.3874	.0000	.0000	.0000	.0001	.10
.11	.3897	.3504	.0000	.0000	.0000	.0002	.11
.12	.3884	.3165	.0000	.0000	.0000	.0004	.12
.13	.3840	.2855	.0000	.0000	.0000	.0006	.13
.14	.3770	.2573	.0000	.0000	.0001	.0009	.14
.15	.3679	.2316	.0000	.0000	.0001	.0012	.15
.16	.3569	.2082	.0000	.0000	.0002	.0018	.16
.17	.3446	.1869	.0000	.0000	.0003	.0024	.17
.18	.3312	.1676	.0000	.0000	.0004	.0032	.18
.19	.3169	.1501	.0000	.0001	.0006	.0043	.19
.20	.3020	.1342	.0000	.0001	.0008	.0055	.20
.21	.2867	.1199	.0000	.0001	.0011	.0070	.21
.22	.2713	.1069	.0000	.0002	.0014	.0088	.22
.23	.2558	.0952	.0000	.0002	.0019	.0109	.23
.24	.2404	.0846	.0000	.0003	.0024	.0134	.24
.25	.2253	.0751	.0000	.0004	.0031	.0162	.25
.26	.2104	.0665	.0000	.0005	.0039	.0195	.26
.27	.1960	.0589	.0001	.0007	.0049	.0231	.27
.28	.1820	.0520	.0001	.0009	.0060	.0272	.28
.29	.1685	.0458	.0001	.0011	.0074	.0317	.29
.30	.1556	.0404	.0001	.0014	.0090	.0368	.30
.31	.1433	.0355	.0002	.0018	.0108	.0422	.31
.32	.1317	.0311	.0002	.0023	.0130	.0482	.32
.33	.1206	.0272	.0003	.0028	.0154	.0547	.33
.34	.1102	.0238	.0004	.0035	.0181	.0616	.34
.35	.1004	.0207	.0005	.0043	.0212	.0689	.35
.36	.0912	.0180	.0006	.0052	.0247	.0767	.36
.37	.0826	.0156	.0008	.0063	.0285	.0849	.37
.38	.0747	.0135	.0010	.0075	.0327	.0934	.38
.39	.0673	.0117	.0013	.0090	.0374	.1023	.39
.40	.0605	.0101	.0016	.0106	.0425	.1115	.40
.41	.0542	.0087	.0019	.0125	.0480	.1209	.41
.42	.0484	.0074	.0024	.0147	.0540	.1304	.42
.43	.0431	.0064	.0029	.0171	.0604	.1401	.43
.44	.0383	.0054	.0035	.0198	.0673	.1499	.44
.45	.0339	.0046	.0042	.0229	.0746	.1596	.45
.46	.0299	.0039	.0050	.0263	.0824	.1692	.46
.47	.0263	.0033	.0059	.0301	.0905	.1786	.47
.48	.0231	.0028	.0070	.0343	.0991	.1878	.48
.49	.0202	.0023	.0083	.0389	.1080	.1966	.49
.50	.0176	.0020	.0098	.0439	.1172	.2051	.50

TABLE A-1. (CONCLUDED)

p	n = 10 r = 5	n = 10 r = 4	n = 10 r = 3	n = 10 r = 2	n = 10 r = 1	n = 10 r = 0	p
.01	.0000	.0000	.0001	.0042	.0914	.9044	.01
.02	.0000	.0000	.0008	.0153	.1667	.8171	.02
.03	.0000	.0001	.0026	.0317	.2281	.7374	.03
.04	.0000	.0004	.0058	.0519	.2770	.6648	.04
.05	.0001	.0010	.0105	.0746	.3151	.5987	.05
.06	.0001	.0019	.0168	.0988	.3438	.5386	.06
.07	.0003	.0033	.0248	.1234	.3643	.4840	.07
.08	.0005	.0052	.0343	.1478	.3777	.4344	.08
.09	.0009	.0078	.0452	.1714	.3851	.3894	.09
.10	.0015	.0112	.0574	.1937	.3874	.3487	.10
.11	.0023	.0153	.0706	.2143	.3854	.3118	.11
.12	.0033	.0202	.0847	.2330	.3798	.2785	.12
.13	.0047	.0260	.0995	.2496	.3712	.2484	.13
.14	.0064	.0326	.1146	.2639	.3603	.2213	.14
.15	.0085	.0401	.1298	.2759	.3474	.1969	.15
.16	.0111	.0483	.1450	.2856	.3331	.1749	.16
.17	.0141	.0573	.1600	.2929	.3178	.1552	.17
.18	.0177	.0670	.1745	.2980	.3017	.1374	.18
.19	.0218	.0773	.1883	.3010	.2852	.1216	.19
.20	.0264	.0881	.2013	.3020	.2684	.1074	.20
.21	.0317	.0993	.2134	.3011	.2517	.0947	.21
.22	.0375	.1108	.2244	.2984	.2351	.0834	.22
.23	.0439	.1225	.2343	.2942	.2188	.0733	.23
.24	.0509	.1343	.2429	.2885	.2030	.0643	.24
.25	.0584	.1460	.2503	.2816	.1877	.0563	.25
.26	.0664	.1576	.2563	.2735	.1730	.0492	.26
.27	.0750	.1689	.2609	.2646	.1590	.0430	.27
.28	.0839	.1798	.2642	.2548	.1456	.0374	.28
.29	.0933	.1903	.2662	.2444	.1330	.0326	.29
.30	.1029	.2001	.2668	.2335	.1211	.0282	.30
.31	.1128	.2093	.2662	.2222	.1099	.0245	.31
.32	.1229	.2177	.2644	.2107	.0995	.0211	.32
.33	.1332	.2253	.2614	.1990	.0898	.0182	.33
.34	.1434	.2320	.2573	.1873	.0808	.0157	.34
.35	.1536	.2377	.2522	.1757	.0725	.0135	.35
.36	.1636	.2424	.2462	.1642	.0649	.0115	.36
.37	.1734	.2461	.2394	.1529	.0578	.0098	.37
.38	.1829	.2487	.2319	.1419	.0514	.0084	.38
.39	.1920	.2503	.2237	.1312	.0456	.0071	.39
.40	.2007	.2508	.2150	.1209	.0403	.0060	.40
.41	.2087	.2503	.2058	.1111	.0355	.0051	.41
.42	.2162	.2488	.1963	.1017	.0312	.0043	.42
.43	.2229	.2462	.1865	.0927	.0273	.0036	.43
.44	.2289	.2427	.1765	.0843	.0238	.0030	.44
.45	.2340	.2384	.1665	.0763	.0207	.0025	.45
.46	.2383	.2331	.1564	.0688	.0180	.0021	.46
.47	.2417	.2271	.1464	.0619	.0155	.0017	.47
.48	.2441	.2204	.1364	.0554	.0133	.0014	.48
.49	.2456	.2130	.1267	.0494	.0114	.0012	.49
.50	.2461	.2051	.1172	.0439	.0098	.0010	.50

TABLE A-2. PARTIAL SUMS

PROBABILITY OF REALIZING $s \geq r$ SUCCESSES IN n TRIALS

$$P(s \geq r/n, p) = \sum_{s=r}^{n} \frac{n!}{s!(n-s)!} p^s q^{n-s}$$

p	n = 2 r = 2	n = 2 r = 1	n = 3 r = 3	n = 3 r = 2	n = 3 r = 1	n = 4 r = 4	p
.01	.0001	.0199	.0000	.0003	.0297	.0000	.01
.02	.0004	.0396	.0000	.0012	.0588	.0000	.02
.03	.0009	.0591	.0000	.0026	.0873	.0000	.03
.04	.0016	.0784	.0001	.0047	.1153	.0000	.04
.05	.0025	.0975	.0001	.0073	.1426	.0000	.05
.06	.0036	.1164	.0002	.0104	.1694	.0000	.06
.07	.0049	.1351	.0003	.0140	.1956	.0000	.07
.08	.0064	.1536	.0005	.0182	.2213	.0000	.08
.09	.0081	.1719	.0007	.0228	.2464	.0001	.09
.10	.0100	.1900	.0010	.0280	.2710	.0001	.10
.11	.0121	.2079	.0013	.0336	.2950	.0001	.11
.12	.0144	.2256	.0017	.0397	.3185	.0002	.12
.13	.0169	.2431	.0022	.0463	.3415	.0003	.13
.14	.0196	.2604	.0027	.0533	.3639	.0004	.14
.15	.0225	.2775	.0034	.0607	.3859	.0005	.15
.16	.0256	.2944	.0041	.0686	.4073	.0007	.16
.17	.0289	.3111	.0049	.0769	.4282	.0008	.17
.18	.0324	.3276	.0058	.0855	.4486	.0010	.18
.19	.0361	.3439	.0069	.0946	.4686	.0013	.19
.20	.0400	.3600	.0080	.1040	.4880	.0016	.20
.21	.0441	.3759	.0093	.1138	.5070	.0019	.21
.22	.0484	.3916	.0106	.1239	.5254	.0023	.22
.23	.0529	.4071	.0122	.1344	.5435	.0028	.23
.24	.0576	.4224	.0138	.1452	.5610	.0033	.24
.25	.0625	.4375	.0156	.1562	.5781	.0039	.25
.26	.0676	.4524	.0176	.1676	.5948	.0046	.26
.27	.0729	.4671	.0197	.1793	.6110	.0053	.27
.28	.0784	.4816	.0220	.1913	.6268	.0061	.28
.29	.0841	.4959	.0244	.2035	.6421	.0071	.29
.30	.0900	.5100	.0270	.2160	.6570	.0081	.30
.31	.0961	.5239	.0298	.2287	.6715	.0092	.31
.32	.1024	.5376	.0328	.2417	.6856	.0105	.32
.33	.1089	.5511	.0359	.2548	.6992	.0119	.33
.34	.1156	.5644	.0393	.2682	.7125	.0134	.34
.35	.1225	.5775	.0429	.2817	.7254	.0150	.35
.36	.1296	.5904	.0467	.2955	.7379	.0168	.36
.37	.1369	.6031	.0507	.3094	.7500	.0187	.37
.38	.1444	.6156	.0549	.3235	.7617	.0209	.38
.39	.1521	.6279	.0593	.3377	.7730	.0231	.39
.40	.1600	.6400	.0640	.3520	.7840	.0256	.40
.41	.1681	.6519	.0689	.3665	.7946	.0283	.41
.42	.1764	.6636	.0741	.3810	.8049	.0311	.42
.43	.1849	.6751	.0795	.3957	.8148	.0342	.43
.44	.1936	.6864	.0852	.4104	.8244	.0375	.44
.45	.2025	.6975	.0911	.4252	.8336	.0410	.45
.46	.2116	.7084	.0973	.4401	.8425	.0448	.46
.47	.2209	.7191	.1038	.4551	.8511	.0488	.47
.48	.2304	.7296	.1106	.4700	.8594	.0531	.48
.49	.2401	.7399	.1176	.4850	.8673	.0576	.49
.50	.2500	.7500	.1250	.5000	.8750	.0625	.50

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TABLE A-2. (CONTINUED)

p	n = 4 r = 3	n = 4 r = 2	n = 4 r = 1	n = 5 r = 5	n = 5 r = 4	n = 5 r = 3	p
.01	.0000	.0006	.0394	.0000	.0000	.0000	.01
.02	.0000	.0023	.0776	.0000	.0000	.0001	.02
.03	.0001	.0052	.1147	.0000	.0000	.0003	.03
.04	.0002	.0091	.1507	.0000	.0000	.0006	.04
.05	.0005	.0140	.1855	.0000	.0000	.0012	.05
.06	.0008	.0199	.2193	.0000	.0001	.0020	.06
.07	.0013	.0267	.2519	.0000	.0001	.0031	.07
.08	.0019	.0344	.2836	.0000	.0002	.0045	.08
.09	.0027	.0430	.3143	.0000	.0003	.0063	.09
.10	.0037	.0523	.3439	.0000	.0005	.0086	.10
.11	.0049	.0624	.3726	.0000	.0007	.0112	.11
.12	.0063	.0732	.4003	.0000	.0009	.0143	.12
.13	.0079	.0847	.4271	.0000	.0013	.0179	.13
.14	.0098	.0968	.4530	.0001	.0017	.0220	.14
.15	.0120	.1095	.4780	.0001	.0022	.0266	.15
.16	.0144	.1228	.5021	.0001	.0029	.0318	.16
.17	.0171	.1366	.5254	.0001	.0036	.0375	.17
.18	.0202	.1509	.5479	.0002	.0045	.0437	.18
.19	.0235	.1656	.5695	.0002	.0055	.0505	.19
.20	.0272	.1808	.5904	.0003	.0067	.0579	.20
.21	.0312	.1963	.6105	.0004	.0081	.0659	.21
.22	.0356	.2122	.6298	.0005	.0097	.0744	.22
.23	.0403	.2285	.6485	.0006	.0114	.0836	.23
.24	.0453	.2450	.6664	.0008	.0134	.0933	.24
.25	.0508	.2617	.6836	.0010	.0156	.1035	.25
.26	.0566	.2787	.7001	.0012	.0181	.1143	.26
.27	.0628	.2959	.7160	.0014	.0208	.1257	.27
.28	.0694	.3132	.7313	.0017	.0238	.1376	.28
.29	.0763	.3307	.7459	.0021	.0272	.1501	.29
.30	.0837	.3483	.7599	.0024	.0308	.1631	.30
.31	.0915	.3660	.7733	.0029	.0347	.1766	.31
.32	.0996	.3837	.7862	.0034	.0390	.1905	.32
.33	.1082	.4015	.7985	.0039	.0436	.2050	.33
.34	.1171	.4193	.8103	.0045	.0486	.2199	.34
.35	.1265	.4370	.8215	.0053	.0540	.2352	.35
.36	.1362	.4547	.8322	.0060	.0598	.2509	.36
.37	.1464	.4724	.8425	.0069	.0660	.2670	.37
.38	.1569	.4900	.8522	.0079	.0726	.2835	.38
.39	.1679	.5075	.8615	.0090	.0796	.3003	.39
.40	.1792	.5248	.8704	.0102	.0870	.3174	.40
.41	.1909	.5420	.8788	.0116	.0949	.3349	.41
.42	.2030	.5590	.8868	.0131	.1033	.3525	.42
.43	.2155	.5759	.8944	.0147	.1121	.3705	.43
.44	.2283	.5926	.9017	.0165	.1214	.3886	.44
.45	.2415	.6090	.9085	.0185	.1312	.4069	.45
.46	.2550	.6252	.9150	.0206	.1415	.4253	.46
.47	.2689	.6412	.9211	.0229	.1522	.4439	.47
.48	.2831	.6569	.9269	.0255	.1635	.4625	.48
.49	.2977	.6724	.9323	.0282	.1752	.4813	.49
.50	.3125	.6875	.9375	.0313	.1875	.5000	.50

TABLE A-2. (CONTINUED)

p	n = 5 r = 2	n = 5 r = 1	n = 6 r = 6	n = 6 r = 5	n = 6 r = 4	n = 6 r = 3	p
.01	.0010	.0490	.0000	.0000	.0000	.0000	.01
.02	.0038	.0961	.0000	.0000	.0000	.0002	.02
.03	.0085	.1413	.0000	.0000	.0000	.0005	.03
.04	.0148	.1846	.0000	.0000	.0000	.0012	.04
.05	.0226	.2262	.0000	.0000	.0001	.0022	.05
.06	.0319	.2661	.0000	.0000	.0002	.0038	.06
.07	.0425	.3043	.0000	.0000	.0003	.0058	.07
.08	.0544	.3409	.0000	.0000	.0005	.0085	.08
.09	.0674	.3760	.0000	.0000	.0008	.0118	.09
.10	.0815	.4095	.0000	.0001	.0013	.0159	.10
.11	.0965	.4416	.0000	.0001	.0018	.0206	.11
.12	.1125	.4723	.0000	.0001	.0025	.0261	.12
.13	.1292	.5016	.0000	.0002	.0034	.0324	.13
.14	.1467	.5296	.0000	.0003	.0045	.0395	.14
.15	.1648	.5563	.0000	.0004	.0059	.0473	.15
.16	.1835	.5818	.0000	.0005	.0075	.0560	.16
.17	.2027	.6061	.0000	.0007	.0094	.0655	.17
.18	.2224	.6293	.0000	.0010	.0116	.0759	.18
.19	.2424	.6513	.0000	.0013	.0141	.0870	.19
.20	.2627	.6723	.0001	.0016	.0170	.0989	.20
.21	.2833	.6923	.0001	.0020	.0202	.1115	.21
.22	.3041	.7113	.0001	.0025	.0239	.1250	.22
.23	.3251	.7293	.0001	.0031	.0280	.1391	.23
.24	.3461	.7464	.0002	.0038	.0326	.1539	.24
.25	.3672	.7627	.0002	.0046	.0376	.1694	.25
.26	.3883	.7781	.0003	.0056	.0431	.1856	.26
.27	.4093	.7927	.0004	.0067	.0492	.2023	.27
.28	.4303	.8065	.0005	.0079	.0557	.2196	.28
.29	.4511	.8196	.0006	.0093	.0628	.2374	.29
.30	.4718	.8319	.0007	.0109	.0705	.2557	.30
.31	.4923	.8436	.0009	.0127	.0787	.2744	.31
.32	.5125	.8546	.0011	.0148	.0875	.2936	.32
.33	.5325	.8650	.0013	.0170	.0969	.3130	.33
.34	.5522	.8748	.0015	.0195	.1069	.3328	.34
.35	.5716	.8840	.0018	.0223	.1174	.3529	.35
.36	.5906	.8926	.0022	.0254	.1286	.3732	.36
.37	.6093	.9008	.0026	.0288	.1404	.3937	.37
.38	.6276	.9084	.0030	.0325	.1527	.4143	.38
.39	.6455	.9155	.0035	.0365	.1657	.4350	.39
.40	.6630	.9222	.0041	.0410	.1792	.4557	.40
.41	.6801	.9285	.0048	.0458	.1933	.4764	.41
.42	.6967	.9344	.0055	.0510	.2080	.4971	.42
.43	.7129	.9398	.0063	.0566	.2232	.5177	.43
.44	.7286	.9449	.0073	.0627	.2390	.5382	.44
.45	.7438	.9497	.0083	.0692	.2553	.5585	.45
.46	.7585	.9541	.0095	.0762	.2721	.5786	.46
.47	.7728	.9582	.0108	.0837	.2893	.5985	.47
.48	.7865	.9620	.0122	.0917	.3070	.6180	.48
.49	.7998	.9655	.0138	.1003	.3252	.6373	.49
.50	.8125	.9687	.0156	.1094	.3437	.6562	.50

TABLE A-2. (CONTINUED)

p	n = 6 r = 2	n = 6 r = 1	n = 7 r = 7	n = 7 r = 6	n = 7 r = 5	n = 7 r = 4	p
.01	.0015	.0585	.0000	.0000	.0000	.0000	.01
.02	.0057	.1142	.0000	.0000	.0000	.0000	.02
.03	.0125	.1670	.0000	.0000	.0000	.0000	.03
.04	.0216	.2172	.0000	.0000	.0000	.0001	.04
.05	.0328	.2649	.0000	.0000	.0000	.0002	.05
.06	.0459	.3101	.0000	.0000	.0000	.0004	.06
.07	.0608	.3530	.0000	.0000	.0000	.0007	.07
.08	.0773	.3936	.0000	.0000	.0001	.0012	.08
.09	.0952	.4321	.0000	.0000	.0001	.0018	.09
.10	.1143	.4686	.0000	.0000	.0002	.0027	.10
.11	.1345	.5030	.0000	.0000	.0003	.0039	.11
.12	.1556	.5356	.0000	.0000	.0004	.0054	.12
.13	.1776	.5664	.0000	.0000	.0006	.0072	.13
.14	.2003	.5954	.0000	.0000	.0009	.0094	.14
.15	.2235	.6229	.0000	.0001	.0012	.0121	.15
.16	.2472	.6487	.0000	.0001	.0017	.0153	.16
.17	.2713	.6731	.0000	.0001	.0022	.0189	.17
.18	.2956	.6960	.0000	.0002	.0029	.0231	.18
.19	.3201	.7176	.0000	.0003	.0037	.0279	.19
.20	.3446	.7379	.0000	.0004	.0047	.0333	.20
.21	.3692	.7569	.0000	.0005	.0058	.0394	.21
.22	.3937	.7748	.0000	.0006	.0072	.0461	.22
.23	.4180	.7916	.0000	.0008	.0088	.0536	.23
.24	.4422	.8073	.0000	.0011	.0107	.0617	.24
.25	.4661	.8220	.0001	.0013	.0129	.0706	.25
.26	.4896	.8358	.0001	.0017	.0153	.0802	.26
.27	.5128	.8487	.0001	.0021	.0181	.0905	.27
.28	.5356	.8607	.0001	.0026	.0213	.1016	.28
.29	.5580	.8719	.0002	.0031	.0248	.1134	.29
.30	.5798	.8824	.0002	.0038	.0288	.1260	.30
.31	.6012	.8921	.0003	.0046	.0332	.1394	.31
.32	.6220	.9011	.0003	.0055	.0380	.1534	.32
.33	.6422	.9095	.0004	.0065	.0434	.1682	.33
.34	.6619	.9173	.0005	.0077	.0492	.1837	.34
.35	.6809	.9246	.0006	.0090	.0556	.1998	.35
.36	.6994	.9313	.0008	.0105	.0625	.2167	.36
.37	.7172	.9375	.0009	.0123	.0701	.2341	.37
.38	.7343	.9432	.0011	.0142	.0782	.2521	.38
.39	.7508	.9485	.0014	.0164	.0869	.2707	.39
.40	.7667	.9533	.0016	.0188	.0963	.2898	.40
.41	.7819	.9578	.0019	.0216	.1063	.3094	.41
.42	.7965	.9619	.0023	.0246	.1169	.3294	.42
.43	.8105	.9657	.0027	.0279	.1282	.3498	.43
.44	.8238	.9692	.0032	.0316	.1402	.3706	.44
.45	.8364	.9723	.0037	.0357	.1529	.3917	.45
.46	.8485	.9752	.0044	.0402	.1663	.4131	.46
.47	.8599	.9778	.0051	.0451	.1803	.4346	.47
.48	.8707	.9802	.0059	.0504	.1951	.4563	.48
.49	.8810	.9824	.0068	.0562	.2105	.4781	.49
.50	.8906	.9844	.0078	.0625	.2266	.5000	.50

TABLE A-2. (CONTINUED)

p	n = 7 r = 3	n = 7 r = 2	n = 7 r = 1	n = 8 r = 8	n = 8 r = 7	n = 8 r = 6	p
.01	.0000	.0020	.0679	.0000	.0000	.0000	.01
.02	.0003	.0079	.1319	.0000	.0000	.0000	.02
.03	.0009	.0171	.1920	.0000	.0000	.0000	.03
.04	.0020	.0294	.2486	.0000	.0000	.0000	.04
.05	.0038	.0444	.3017	.0000	.0000	.0000	.05
.06	.0063	.0618	.3515	.0000	.0000	.0000	.06
.07	.0097	.0813	.3983	.0000	.0000	.0000	.07
.08	.0140	.1026	.4422	.0000	.0000	.0000	.08
.09	.0193	.1255	.4832	.0000	.0000	.0000	.09
.10	.0257	.1497	.5217	.0000	.0000	.0000	.10
.11	.0331	.1750	.5577	.0000	.0000	.0000	.11
.12	.0416	.2012	.5913	.0000	.0000	.0001	.12
.13	.0513	.2281	.6227	.0000	.0000	.0001	.13
.14	.0620	.2556	.6521	.0000	.0000	.0002	.14
.15	.0738	.2834	.6794	.0000	.0000	.0002	.15
.16	.0866	.3115	.7049	.0000	.0000	.0003	.16
.17	.1005	.3396	.7286	.0000	.0000	.0005	.17
.18	.1154	.3677	.7507	.0000	.0000	.0007	.18
.19	.1313	.3956	.7712	.0000	.0001	.0009	.19
.20	.1480	.4233	.7903	.0000	.0001	.0012	.20
.21	.1657	.4506	.8080	.0000	.0001	.0016	.21
.22	.1841	.4775	.8243	.0000	.0002	.0021	.22
.23	.2033	.5040	.8395	.0000	.0002	.0027	.23
.24	.2231	.5298	.8535	.0000	.0003	.0034	.24
.25	.2436	.5551	.8665	.0000	.0004	.0042	.25
.26	.2646	.5796	.8785	.0000	.0005	.0052	.26
.27	.2861	.6035	.8895	.0000	.0006	.0064	.27
.28	.3081	.6266	.8997	.0000	.0008	.0078	.28
.29	.3304	.6490	.9090	.0001	.0010	.0094	.29
.30	.3529	.6706	.9176	.0001	.0013	.0113	.30
.31	.3757	.6914	.9255	.0001	.0016	.0134	.31
.32	.3987	.7113	.9328	.0001	.0020	.0159	.32
.33	.4217	.7304	.9394	.0001	.0024	.0187	.33
.34	.4447	.7487	.9454	.0002	.0030	.0218	.34
.35	.4677	.7662	.9510	.0002	.0036	.0253	.35
.36	.4906	.7828	.9560	.0003	.0043	.0293	.36
.37	.5134	.7987	.9606	.0004	.0051	.0336	.37
.38	.5359	.8137	.9648	.0004	.0061	.0385	.38
.39	.5581	.8279	.9686	.0005	.0072	.0439	.39
.40	.5801	.8414	.9720	.0007	.0085	.0498	.40
.41	.6017	.8541	.9751	.0008	.0100	.0563	.41
.42	.6229	.8660	.9779	.0010	.0117	.0634	.42
.43	.6436	.8772	.9805	.0012	.0136	.0711	.43
.44	.6638	.8877	.9827	.0014	.0157	.0794	.44
.45	.6836	.8976	.9848	.0017	.0181	.0885	.45
.46	.7027	.9068	.9866	.0020	.0208	.0982	.46
.47	.7213	.9153	.9883	.0024	.0239	.1086	.47
.48	.7393	.9233	.9897	.0028	.0272	.1198	.48
.49	.7567	.9307	.9910	.0033	.0310	.1318	.49
.50	.7734	.9375	.9922	.0039	.0352	.1445	.50

TABLE A-2. (CONTINUED)

p	n = 8 r = 5	n = 8 r = 4	n = 8 r = 3	n = 8 r = 2	n = 8 r = 1	n = 9 r = 9	p
.01	.0000	.0000	.0001	.0027	.0773	.0000	.01
.02	.0000	.0000	.0004	.0103	.1492	.0000	.02
.03	.0000	.0001	.0013	.0223	.2163	.0000	.03
.04	.0000	.0002	.0031	.0381	.2786	.0000	.04
.05	.0000	.0004	.0058	.0572	.3366	.0000	.05
.06	.0000	.0007	.0096	.0792	.3904	.0000	.06
.07	.0001	.0013	.0147	.1035	.4404	.0000	.07
.08	.0001	.0022	.0211	.1298	.4868	.0000	.08
.09	.0003	.0034	.0289	.1577	.5297	.0000	.09
.10	.0004	.0050	.0381	.1869	.5695	.0000	.10
.11	.0007	.0071	.0487	.2171	.6063	.0000	.11
.12	.0010	.0097	.0608	.2480	.6404	.0000	.12
.13	.0015	.0129	.0743	.2794	.6718	.0000	.13
.14	.0021	.0168	.0891	.3111	.7008	.0000	.14
.15	.0029	.0214	.1052	.3428	.7275	.0000	.15
.16	.0038	.0267	.1226	.3744	.7521	.0000	.16
.17	.0050	.0328	.1412	.4057	.7748	.0000	.17
.18	.0065	.0397	.1608	.4366	.7956	.0000	.18
.19	.0083	.0476	.1815	.4670	.8147	.0000	.19
.20	.0104	.0563	.2031	.4967	.8322	.0000	.20
.21	.0129	.0659	.2255	.5257	.8483	.0000	.21
.22	.0158	.0765	.2486	.5538	.8630	.0000	.22
.23	.0191	.0880	.2724	.5811	.8764	.0000	.23
.24	.0230	.1004	.2967	.6075	.8887	.0000	.24
.25	.0273	.1138	.3215	.6329	.8999	.0000	.25
.26	.0322	.1281	.3465	.6573	.9101	.0000	.26
.27	.0377	.1433	.3718	.6807	.9194	.0000	.27
.28	.0438	.1594	.3973	.7031	.9278	.0000	.28
.29	.0505	.1763	.4228	.7244	.9354	.0000	.29
.30	.0580	.1941	.4482	.7447	.9424	.0000	.30
.31	.0661	.2126	.4736	.7640	.9486	.0000	.31
.32	.0750	.2319	.4987	.7822	.9543	.0000	.32
.33	.0846	.2519	.5236	.7994	.9594	.0000	.33
.34	.0949	.2724	.5481	.8156	.9640	.0001	.34
.35	.1061	.2936	.5722	.8309	.9681	.0001	.35
.36	.1180	.3153	.5958	.8452	.9719	.0001	.36
.37	.1307	.3374	.6189	.8586	.9752	.0001	.37
.38	.1443	.3599	.6415	.8711	.9782	.0002	.38
.39	.1586	.3828	.6634	.8828	.9808	.0002	.39
.40	.1737	.4059	.6846	.8936	.9832	.0003	.40
.41	.1895	.4292	.7052	.9037	.9853	.0003	.41
.42	.2062	.4527	.7250	.9130	.9872	.0004	.42
.43	.2235	.4762	.7440	.9216	.9889	.0005	.43
.44	.2416	.4996	.7624	.9295	.9903	.0006	.44
.45	.2604	.5230	.7799	.9368	.9916	.0008	.45
.46	.2798	.5463	.7966	.9435	.9928	.0009	.46
.47	.2999	.5694	.8125	.9496	.9938	.0011	.47
.48	.3205	.5922	.8276	.9552	.9947	.0014	.48
.49	.3416	.6146	.8419	.9602	.9954	.0016	.49
.50	.3633	.6367	.8555	.9648	.9961	.0020	.50

TABLE A-2. (CONTINUED)

p	n = 9 r = 8	n = 9 r = 7	n = 9 r = 6	n = 9 r = 5	n = 9 r = 4	n = 9 r = 3	p
.01	.0000	.0000	.0000	.0000	.0000	.0001	.01
.02	.0000	.0000	.0000	.0000	.0000	.0006	.02
.03	.0000	.0000	.0000	.0000	.0001	.0020	.03
.04	.0000	.0000	.0000	.0000	.0003	.0045	.04
.05	.0000	.0000	.0000	.0000	.0006	.0084	.05
.06	.0000	.0000	.0000	.0001	.0013	.0138	.06
.07	.0000	.0000	.0000	.0002	.0023	.0209	.07
.08	.0000	.0000	.0000	.0003	.0037	.0298	.08
.09	.0000	.0000	.0000	.0005	.0057	.0405	.09
.10	.0000	.0000	.0001	.0009	.0083	.0530	.10
.11	.0000	.0000	.0001	.0014	.0117	.0672	.11
.12	.0000	.0000	.0002	.0021	.0158	.0833	.12
.13	.0000	.0000	.0003	.0030	.0209	.1009	.13
.14	.0000	.0000	.0004	.0041	.0269	.1202	.14
.15	.0000	.0000	.0006	.0056	.0339	.1409	.15
.16	.0000	.0001	.0009	.0075	.0420	.1629	.16
.17	.0000	.0001	.0013	.0098	.0512	.1861	.17
.18	.0000	.0002	.0017	.0125	.0615	.2105	.18
.19	.0000	.0002	.0023	.0158	.0730	.2357	.19
.20	.0000	.0003	.0031	.0196	.0856	.2618	.20
.21	.0000	.0004	.0040	.0240	.0994	.2885	.21
.22	.0000	.0006	.0051	.0291	.1144	.3158	.22
.23	.0001	.0008	.0065	.0350	.1304	.3434	.23
.24	.0001	.0010	.0081	.0416	.1475	.3713	.24
.25	.0001	.0013	.0100	.0489	.1657	.3993	.25
.26	.0001	.0017	.0122	.0571	.1849	.4273	.26
.27	.0002	.0022	.0149	.0662	.2050	.4552	.27
.28	.0003	.0028	.0179	.0762	.2260	.4829	.28
.29	.0003	.0035	.0213	.0870	.2478	.5102	.29
.30	.0004	.0043	.0253	.0988	.2703	.5372	.30
.31	.0006	.0053	.0298	.1115	.2935	.5636	.31
.32	.0007	.0064	.0348	.1252	.3173	.5894	.32
.33	.0009	.0078	.0404	.1398	.3415	.6146	.33
.34	.0011	.0094	.0467	.1553	.3662	.6390	.34
.35	.0014	.0112	.0536	.1717	.3911	.6627	.35
.36	.0017	.0133	.0612	.1890	.4163	.6856	.36
.37	.0021	.0157	.0696	.2072	.4416	.7076	.37
.38	.0026	.0184	.0787	.2262	.4669	.7287	.38
.39	.0031	.0215	.0886	.2460	.4922	.7489	.39
.40	.0038	.0250	.0994	.2666	.5174	.7682	.40
.41	.0046	.0290	.1109	.2878	.5424	.7866	.41
.42	.0055	.0334	.1233	.3097	.5670	.8039	.42
.43	.0065	.0383	.1366	.3322	.5913	.8204	.43
.44	.0077	.0437	.1508	.3551	.6152	.8359	.44
.45	.0091	.0498	.1658	.3786	.6386	.8505	.45
.46	.0107	.0564	.1817	.4024	.6614	.8642	.46
.47	.0125	.0637	.1985	.4265	.6836	.8769	.47
.48	.0145	.0717	.2161	.4509	.7052	.8889	.48
.49	.0169	.0804	.2346	.4754	.7260	.8999	.49
.50	.0195	.0898	.2539	.5000	.7461	.9102	.50

TABLE A-2. (CONTINUED)

p	n = 9 r = 2	n = 9 r = 1	n = 10 r = 10	n = 10 r = 9	n = 10 r = 8	n = 10 r = 7	p
.01	.0034	.0865	.0000	.0000	.0000	.0000	.01
.02	.0131	.1663	.0000	.0000	.0000	.0000	.02
.03	.0282	.2398	.0000	.0000	.0000	.0000	.03
.04	.0478	.3075	.0000	.0000	.0000	.0000	.04
.05	.0712	.3698	.0000	.0000	.0000	.0000	.05
.06	.0978	.4270	.0000	.0000	.0000	.0000	.06
.07	.1271	.4796	.0000	.0000	.0000	.0000	.07
.08	.1583	.5278	.0000	.0000	.0000	.0000	.08
.09	.1912	.5721	.0000	.0000	.0000	.0000	.09
.10	.2252	.6126	.0000	.0000	.0000	.0000	.10
.11	.2599	.6496	.0000	.0000	.0000	.0000	.11
.12	.2951	.6835	.0000	.0000	.0000	.0000	.12
.13	.3304	.7145	.0000	.0000	.0000	.0001	.13
.14	.3657	.7427	.0000	.0000	.0000	.0001	.14
.15	.4005	.7684	.0000	.0000	.0000	.0001	.15
.16	.4348	.7918	.0000	.0000	.0000	.0002	.16
.17	.4685	.8131	.0000	.0000	.0000	.0003	.17
.18	.5012	.8324	.0000	.0000	.0000	.0004	.18
.19	.5330	.8499	.0000	.0000	.0001	.0006	.19
.20	.5638	.8658	.0000	.0000	.0001	.0009	.20
.21	.5934	.8801	.0000	.0000	.0001	.0012	.21
.22	.6218	.8931	.0000	.0000	.0002	.0016	.22
.23	.6491	.9048	.0000	.0000	.0002	.0021	.23
.24	.6750	.9154	.0000	.0000	.0003	.0027	.24
.25	.6997	.9249	.0000	.0000	.0004	.0035	.25
.26	.7230	.9335	.0000	.0000	.0006	.0045	.26
.27	.7452	.9411	.0000	.0001	.0007	.0056	.27
.28	.7660	.9480	.0000	.0001	.0010	.0070	.28
.29	.7856	.9542	.0000	.0001	.0012	.0087	.29
.30	.8040	.9596	.0000	.0001	.0016	.0106	.30
.31	.8212	.9645	.0000	.0002	.0020	.0129	.31
.32	.8372	.9689	.0000	.0003	.0025	.0155	.32
.33	.8522	.9728	.0000	.0003	.0032	.0185	.33
.34	.8661	.9762	.0000	.0004	.0039	.0220	.34
.35	.8789	.9793	.0000	.0005	.0048	.0260	.35
.36	.8908	.9820	.0000	.0007	.0059	.0305	.36
.37	.9017	.9844	.0000	.0009	.0071	.0356	.37
.38	.9118	.9865	.0001	.0011	.0086	.0413	.38
.39	.9210	.9883	.0001	.0014	.0103	.0477	.39
.40	.9295	.9899	.0001	.0017	.0123	.0548	.40
.41	.9372	.9913	.0001	.0021	.0146	.0626	.41
.42	.9442	.9926	.0002	.0025	.0172	.0712	.42
.43	.9505	.9936	.0002	.0031	.0202	.0806	.43
.44	.9563	.9946	.0003	.0037	.0236	.0908	.44
.45	.9615	.9954	.0003	.0045	.0274	.1020	.45
.46	.9662	.9961	.0004	.0054	.0317	.1141	.46
.47	.9704	.9967	.0005	.0065	.0366	.1271	.47
.48	.9741	.9972	.0006	.0077	.0420	.1410	.48
.49	.9775	.9977	.0008	.0091	.0480	.1560	.49
.50	.9805	.9980	.0010	.0107	.0547	.1719	.50

TABLE A-2. (CONCLUDED)

p	n = 10 r = 6	n = 10 r = 5	n = 10 r = 4	n = 10 r = 3	n = 10 r = 2	n = 10 r = 1	p
.01	.0000	.0000	.0000	.0001	.0043	.0956	.01
.02	.0000	.0000	.0000	.0009	.0162	.1829	.02
.03	.0000	.0000	.0001	.0028	.0345	.2626	.03
.04	.0000	.0000	.0004	.0062	.0582	.3352	.04
.05	.0000	.0001	.0010	.0115	.0861	.4013	.05
.06	.0000	.0002	.0020	.0188	.1176	.4614	.06
.07	.0000	.0003	.0036	.0283	.1517	.5160	.07
.08	.0000	.0006	.0058	.0401	.1879	.5656	.08
.09	.0001	.0010	.0088	.0540	.2254	.6106	.09
.10	.0001	.0016	.0128	.0702	.2639	.6513	.10
.11	.0003	.0025	.0178	.0884	.3028	.6882	.11
.12	.0004	.0037	.0239	.1087	.3417	.7215	.12
.13	.0006	.0053	.0313	.1308	.3804	.7516	.13
.14	.0010	.0073	.0400	.1545	.4184	.7787	.14
.15	.0014	.0099	.0500	.1798	.4557	.8031	.15
.16	.0020	.0130	.0614	.2064	.4920	.8251	.16
.17	.0027	.0168	.0741	.2341	.5270	.8448	.17
.18	.0037	.0213	.0883	.2628	.5608	.8626	.18
.19	.0049	.0266	.1039	.2922	.5932	.8784	.19
.20	.0064	.0328	.1209	.3222	.6242	.8926	.20
.21	.0082	.0399	.1391	.3526	.6536	.9053	.21
.22	.0104	.0479	.1587	.3831	.6815	.9166	.22
.23	.0130	.0569	.1794	.4137	.7079	.9267	.23
.24	.0161	.0670	.2012	.4442	.7327	.9357	.24
.25	.0197	.0781	.2241	.4744	.7560	.9437	.25
.26	.0239	.0904	.2479	.5042	.7778	.9508	.26
.27	.0287	.1037	.2726	.5335	.7981	.9570	.27
.28	.0342	.1181	.2979	.5622	.8170	.9626	.28
.29	.0404	.1337	.3239	.5901	.8345	.9674	.29
.30	.0473	.1503	.3504	.6172	.8507	.9718	.30
.31	.0551	.1679	.3772	.6434	.8656	.9755	.31
.32	.0637	.1867	.4044	.6687	.8794	.9789	.32
.33	.0732	.2064	.4316	.6930	.8920	.9818	.33
.34	.0836	.2270	.4589	.7162	.9035	.9843	.34
.35	.0949	.2485	.4862	.7384	.9140	.9865	.35
.36	.1072	.2708	.5132	.7595	.9236	.9885	.36
.37	.1205	.2939	.5400	.7794	.9323	.9902	.37
.38	.1348	.3177	.5664	.7983	.9402	.9916	.38
.39	.1500	.3420	.5923	.8160	.9473	.9929	.39
.40	.1662	.3669	.6177	.8327	.9536	.9940	.40
.41	.1834	.3922	.6425	.8483	.9594	.9949	.41
.42	.2016	.4178	.6665	.8628	.9645	.9957	.42
.43	.2207	.4436	.6898	.8764	.9691	.9964	.43
.44	.2407	.4696	.7123	.8889	.9731	.9970	.44
.45	.2616	.4956	.7340	.9004	.9767	.9975	.45
.46	.2832	.5216	.7547	.9111	.9799	.9979	.46
.47	.3057	.5474	.7745	.9209	.9827	.9983	.47
.48	.3288	.5730	.7933	.9298	.9852	.9986	.48
.49	.3526	.5982	.8112	.9379	.9874	.9988	.49
.50	.3770	.6230	.8281	.9453	.9893	.9990	.50

APPENDIX B
TECHNIQUES FR SIMULATION TESTNG

B-1. Simulation techniques.

a. The catalog of techniques that follows was compiled primarily from two sources. "Nuclear Blast and Shock Simulators," a report (GE-TEMPO, 1972) by Panel N-2 of the Tripartite Technical Cooperation Programme (whose member nations are the United States, Canada, and the United Kingdom), contains descriptions of tests from which summaries have been tabulated herein. The second source was Rowan (1974) which tabulates other items besides airblast and ground motion that are common to the TTCP report. Specifically, there are sections relating to simulation of nuclear radiation, spallation impulse, thermal radiation, EMP, and debris. While a bit dated in some cases, it is still a worthwhile compilation from which future work may proceed. Additional references are listed in the bibliography, appendix D, grouped into categories pertinent to testing for nuclear weapon effects.

b. An extensive catalog of techniques is presented in tables B-1 through B-10. Recommended test concepts range from laboratory and simple in-plant tests to numberous field tests that can stimulate all or portions of the nuclear environment experienced by major components and subsystems of a facility. Laboratory and in plant test concepts. However, experience with field tests is limited; the cost of field tests will generally be high.

c. The important test comcepts considered are as follows:

- High-Explosive Simulation Technique (HEST)
- Direct-Induced High-Explosive Simulation Technique (DIEHEST)
- High-Explosive Contact Surface Burst
- Underground Nuclear Tamped Burst
- Underground Nuclear Tunnel Test
- Giant Reusable Air-Blast Simulator (GRABS)
- EMP Simulation Testing
- Blast Simulation Technique for Testing Air Entrainment Systems and Blast Closures.

The following subsections discuss these critical test concepts in greater detail than is possible in the catalog presented as tables. More detailed evaluation and development of each of these test concepts is necessary in order to select the appropriate hardness verification test procedures for a postulated nuclear burst.

B-2. High-explosive simulation technique

a. The HEST concept has been used four times for tests on operational Minuteman sites. The technique had been expanded for high-overpressure tests in a rock medium. Periodically, variations of the HEST test are utilized for special applications. The reader is urged to review the current literature to determine whether recent tests have relevance to his application. A summary of HEST experiments from 1964 to 1974 is listed in table B-11.

b. The objective of the technique is to simulate the overpressure and superseismic air-induced ground shock from a nuclear detonation Operational and small scale tests have demonstrated the feasibility of simulating overpressures (for about the first 200 msec) from yields up to 10 Mt and for overpressures up to 3000 psi.

c. HEST uses a confined detonation of explosive fuse (Primacord) to produce a pressure pulse designed to travel over the ground surface at the same velocity as an air shock wave of equal intensity, and to have a timedecay shape similar to the early part of the pressure pulse produced by a nuclear detonation. A HEST facility consists of a platform structure constructed above the surface of the ground over the installation to be tested. (See figure 4-1 for facility configuaration.) The platform supports an overburden of earth and forms a cavity between the bottom of the overburden and the ground. An earthen embankment is built around the perimeter of the platform. Primacord is wrapped on wooden racks that are suspended in the cavity. Since Primacord detonates at a velocity greater than the shock front velocity to be simulated, the cord is wrapped at an angle to the direction of propagation. The intensity of the pressure pulse depends primarily on the loading density (amount of explosives per unit cavity volume). The overburden placed over the HEST platform is compressed and accelerated upward when the overpressure acts on its base, and this upward motion of the overburden causes the volume of the cavity to expand, with a corresponding decrease in pressure.

d. Operational HEST tests have used a cavity that is normally 300 ft. sq. For HEST III the cavity was 5.5 ft deep and the overburden was about 10 ft thick. Primacord charge density was 0.070 lb of explosive per cubic foot of cavity, and the Primacord weave angle was 8 deg 27 min.

Table B-1. Dynamic Pressure Tests Using Shock Tubes to Simulate Airblast Effect

TABLE B-1. DYNAMIC PRESSURE TESTS USING SHOCK TUBES TO SIMULATE AIRBLAST EFFECT

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
DASACON U.S. Naval Weapons Laboratory Dahlgren, VA	Conical high-explosive-driven shock tube. Probably the world's largest (2455 ft long).	Test section 7.5. ft x 10 ft dia., 5.5 bar (80 psi), 300 ms. Test section 9 ft x 15 ft dia., 2.7 bar (40 psi), 500 ms. Test section 12 ft x 22 ft dia., 1.4 bar (20 psi), 500 ms.	Air-blast loading on full-scale and small models. For model sections of 10-ft dia. and below, altitude simulation up to 10^5 ft is available.	Time dependent measurements of: Overpressure Dynamic Pressure Acceleration Velocity/ Displacement Strain Video camera and recorder. The above results are available as analog or magnetic tape. High-speed cine camera film (up to 10,000 fps).
URS Shock Tunnel San Francisco, CA	Rectangular explosively-driven reinforced concrete shock tube. Expansion chamber 8.5 ft x 12 ft x 92 ft long. Driver chamber 8.5 ft x 8 ft x 63 ft	Test section 8.5 ft by 12 ft dia., 40 ft long. Overpressure range 0.1 to 0.75 bar (1.5 to 11 psi). Duration range: 80 to 50 ms.	Frontal air-blast loading on structural elements.	Time dependent measurements of: Overpressure Dynamic Pressure Results on magnetic tape and high-speed cine cameras 1000 fps color, 2000 fps black and white.
BRL, Aberdeen Proving Ground, MD	84 ft x 500 ft total length Compressed air-driven dual shock tube. Can be used either (a) as a separate shock tube or (b) with the expansion chamber joined to the 5.5 ft dia. shock tube (see below), joined through a large air breathing engine as a dual shock tube to test the behavior of such engines under shock loading.	Test section 8 ft dia. No target fixing facilities--each target to be secured to test section walls. Overpressure range: 0.3 to 1.8 bars (3 to 26 psi). 1 sec approx.	Air-blast loading on full-scale and small models. Simultaneous internal blast loading from inlet to outlet of air breathing engines	Time dependent measurements of: Overpressure Dynamic Pressure No high-speed cine facilities.
BRL, Aberdeen Proving Ground, MD	5.5-ft-dia. x 610 ft air-driven shock tube. Driven gas can be heated to eliminate density change on expansion of driven air.	Test section 5.5 ft dia. Remaining details as for the 8 ft dia. tubes.	As above.	As above.

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TABLE B-1. (CONTINUED)

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
AFWL Kirtland AFB, NM	6 ft dia. x 245 ft cylindrical high-explosive-driven shock tube.	Test section flat platform 5 ft x 8 ft with 4.5 ft headroom. Overpressure range up to 7 bars (100 psi). Duration: 100 to 200 ms.	Ground shock and related studies. Air-blast loading.	As above.
Sandia Labs Albuquerque, NM	19-ft-dia. high-explosive-driven blast tunnel. 6 ft dia. x 50 ft driver. 6 ft x 150 ft expansion. 40 ft divergent section. 19 ft dia. x 66 ft expansion section.	Test section 66 ft x 19 ft dia. Initial pressure in the test section can be varied from 1 psia to 12 psia. At 12 psia, static overpressure varies between 1 to 6 bars (14 to 87 psi). Duration: 25 to 50 ms.	Large military units at large angles of attack.	Time-dependent measurements of: Overpressure Dynamic Pressure Stagnation Press. Acceleration Displacement Strain Velocity Results on magnetic tape. High-speed cine camera film up to 8,000 fps.
Sandia Labs Albuquerque, NM	6-ft-dia. x 200-ft high explosive-driven shock tube.	Test section 6-ft dia., target suspended by straps, released just before shock wave arrival, and loaded in free fall. Test section ambient pressures from 0.013 bar (0.2 psia). At ambient of 0.8 bars, overpressure range is 6 to 14 bars (87 to 200 psi). Duration: ∿ 6 ms.	Small military structures	As for the 19 ft dia.
	6-ft-dia. x 50-ft-high-explosive-driven shock tube. Expendable driven section.	Test section 6-ft-dia. Target accommodation as for 200-ft tube above. Test section ambient pressure, 0.07 bar, overpressure 10 bars (145 psi). Duration: 2 to 8 ms.	As above.	As for 19 ft dia.
Lovelace DNA Kirtland AFB, Albuquerque, NM	Cylindrical compressed-air-driven shock tube. 3.5 ft x 15 ft compression chamber, 3.5 ft x 125 ft exp. chamber. 6 ft x 30 ft exp. chamber. 9 ft long coupling sect.	Test section (s) 65 ft by 3.5 ft dia. Overpressure: 0 to 2.3 bars (0 to 33 psi). Duration 100 ms on end plate terminating the tube.	Effect of long-duration airblast on a variety of large animal species.	Time dependent measurements of: Overpressure Dynamic Pressure Photography Oscillograph and Chart Recorders

TABLE B-1. (CONCLUDED)

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
DRES Ralston, Alberta, Canada	6-ft-dia. high-explosive-driven shock tube. Driven from RDX/TNT in a gun barrel, or Primacord line or grid charge at entrance to expansion chamber. 16 in. naval gun with 165 in. long x 6 ft dia. expans. chamber. 57 ft x 16 in. permits recoilless operation.	Test sections all 6 ft dia. Overpressure: 0.1 to 2.4 bars (1.4 to 35 psi). Duration: 50 to 70 ms.	Blast loading. A. High pressure structural response studies. B. Soil medium studies. C. Tests on military equipment and material. D. Tests on targets in normal reflection mode.	Time dependent measurements of: Overpressure Dynamic Pressure Acceleration Velocity Displacement Strain High-Speed Cine (20,000 fps) 17-in. Shadowgraph Video camera and Recorder
DRES Ralston, Alberta, Canada	3-ft-dia. compressed-air or high-explosive-driven shock tube. Driver section similar to 6 ft dia. model, but uses a 14-in naval canon barrel. Approx 175 ft.	Test section 6 ft x 3-ft dia. Compressed Air Driven. Overpressure 0.5 to 1.0 bars (2 to 14 psi). Duration: 200 ms. RDX/TNT Driven. Overpressure 1.1 to 7.0 bars (15 to 100 psi). Duration: 50 to 100 ms.	Tests on military equipment and material and dynamic loading effects.	Time dependent measurements of: Overpressure Dynamic Pressure Acceleration Velocity Displacement Strain High-Speed Cine (20,000 fps) 17 in. Shadowgraph Video camera and Recorder
AFWL Kirtland AFB, Albuquerque, NM	13-in. dia. driven by explosive hydrogen and oxygen gas mixture; Approx 220 ft over all length.	Test section approx 2 ft x 13-in. dia. Overpressure range 3.5 to 45 bars (50 to 650 psi). Duration: 1 to 4 ms.	High-pressure tests of Air Force targets.	Pressure-Time oscillographs
BRL Aberdeen Proving Ground, MD	8-in. dia. detonation-driven shock tube. Hydrogen-oxygen driver mixture.	Test section 55 ft x 22-in. dia. Overpressure 14 bars (200 psi). Duration: 50 ms.	High-pressure loading.	Oscillographs, chart, and tape recorders.
Boeing/SAMSO, Boeing Tulalip Test Site, Tulalip, Wash.	24 in., 36 in., and 30 in. x 52 in. tubes of undetermined length	No data at hand.	--	--
NOL Silver Springs, Maryland	Conical shock tube.	16-in. dia. test section at 75 ft; 24-in. dia. test section at 135 ft.	--	--

Table B-2. Ground Shock Using Blast Load Generators to Simulate Airblast Effect

TABLE B-2. GROUND SHOCK USING BLAST LOAD GENERATORS TO SIMULATE AIRBLAST EFFECT

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
WES Vicksburg, MS	Large blast load generator (LBLG).	Soil loading test section surface area 410 ft^2. Maximum available depth of burial 10 ft. Pressure to 70 bars (1000 psi). Duration: to 2 sec.	Tests for studies in the design and analysis of underground structures.	Time dependent measurements of: Overpressure Soil Stress Acceleration Velocity Displacement Strain Magnetic Tape Records.
	4-ft dia. blast load generator.	Static pressures up to 135 bars (2000 psi) of compressed air or water. Dynamic pressures to 17 bars (250 psi). Durations: to 2 sec.	Testing small buried structures, stress wave propagation, and soil structure interaction.	As above.
	Static loading device.	Static pressure to 410 bars (6000 psi).	Static loading of buried model structures, structural elements, and submerged objects.	Static measurements of: Fluid Pressure Soil Stress Displacement and Strain
Waterways Experimental Station Vicksburg, MS	Vertical detonatable gas shock tube.	Peak pressures 55 to 105 bars (800 to 1500 psi). Durations 3 to 6 ms. Test Chambers: 46.7 in. dia. Depth: (a) 1.75 ft. (b) 4 ft. (c) 5.75 ft.	Shot duration pressure pulses on buried model structures and structural elements.	Time-dependent measurements of: Pressure Soil Stress Acceleration Strain Magnetic Tape Records.
NCEL Port Hueneme, CA	Blast simulator, Primacord driven.	Test pit: 9 ft wide x 10 ft long x 12 ft deep. Peak Pressures: 2 to 14 bars (30 to 200 psi). Duration: 0.4 to 7.0 sec.	Static and dynamic loads on structural elements such as beams, slabs, and model elements.	Time-dependent measurements of: Pressure and Strain Oscillograph Records.
AFWL Kirtland AFB Albuquerque, NM	2-ft-dia. (0.6 m) high-explosive-driven vertical shock tubes.	Test pit: 4 ft deep x 2 ft dia. Surface loading. Peak Overpressure 0.35 to 35 bars (5 to 500 psi). Duration: 30 ms.	Instrumentation development, proof, and testing	Time-dependent measurements of: Soil Pressure
GRABS Air Force Weapons Laboratory Kirtland AFB, NM	Explosive cavity above soil sample in large reinforced concrete-lined silo.	18-ft-dia. x 48-ft-deep silo, soil test bed up to 30 ft of depth possible. Up to 1800 psi overpressure possible.	Buried systems or models of systems, and soil/structure interactions.	See for discussion of GRABS technique.

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Table B-3. Dynamic Loading of Material Using Special Test Machines to Simulate Airblast Effect

TABLE B-3. DYNAMIC LOADING OF MATERIAL USING SPECIAL TEST MACHINES TO SIMULATE AIRBLAST EFFECT

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
Wyle Laboratories Norco, Calif.	Parallel Pendulum Impact.	Velocity peak 400 in./sec.	Shock testing pieces of equipment or of shock-mounted systems	--
	Hammer shock machine	Velocity peak 200 in./sec.	As above.	--
Kirtland AFB Albuquerque, NM	HYGE shock tester	200 g max Duration: 10-50 ms. Peak force: 47,000 lb Wave shape: 1/2 sine square, triangle	As above.	--
Anywhere	Quick-release twang test, from small lab tests to full-scale simulation	Simulates motion by displacement of platform rather than supports.	Shock-isolated platform evaluation tests. Very effective when properly conducted.	--
WES Vicksburg, MS	500-kip ram loader.	Hydraulic actuator, pump, and control system can apply loads in excess of 350,000 lb with approx 1/4-in movement and 80 ms rise-time.	Applies loads to construction materials and structural elements where it is necessary to achieve slowly applied cyclic or random loads.	Time-dependent measurements of: Load Strain Acceleration Velocity Displacement d.c. to 40 kHz FM magnetic recorders
	200-kip dynamic ram loader.	Hydraulic ram applies 10,000 to 20,000 lb in either tension or compression, either slowly or within 2 ms.	Tests structural elements and determines strength of materials under slow static or dynamic loads.	Time-dependent measurements of: Load Strain Acceleration Velocity Displacement d.c. to 40 kHz FM magnetic recording
NCEL, Port Hueneme, CA	50-kip ram loader.	Max force: 50,000 lb. Rise time: 2 to 200 ms. Duration: 0 to 2 sec. Head velocity: 3 to 1800 in./min.	Dynamic testing of metal, concrete, and other material specimens.	Time-dependent measurements of: Head displacement Strain Head resistance d.c. to kHz FM magnetic recording
AFWL Albuquerque, NM	50-kip ram loader.	Pneumatic-hydraulic driver, 100 to 50,000 lb. Nominal 59,000-lb maximum. Rise time: 1.5 to 50 ms. Duration: 20 ms to 30 sec. Velocity: 4 in./min to 450 in./min. Test section: 14-to 74-in. wide by 48 in. Used either force-time or constant velocity loader.	Dynamic testing of properties of materials.	Refer to AFWL.

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TABLE B-3. (CONCLUDED)

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
WES Vicksburg, MS	Dynamic triaxial test apparatus.	Compressed-gas vertical-load generator 10- to 5000-lb load, 4-in. stroke, 10 ms to 1 sec time to failure.	Dynamic testing to determine shear strength of soils.	Time-dependent measurements of: Top load Bottom load Top displacement
WES Vicksburg, MS	Dynamic load-test systems.	Compressed-gas loaders apply controlled impulse or static loads 100 to 115,000 lb on test specimens up to 8-ft wide by 50-in high.	To determine response of earth materials and soil structure systems to high amplitude impulse loading (nuclear blast simulation).	Time-dependent measurements of: Force generation Uniaxial strain Vertical fluid pressures Displacements Triaxial chamber pressures Vertical load Vertical and horizontal displacements on triaxial specimens. Oscillograph and analog-tape recording.
	Explosive-test facility.	Explosive plane-wave lens system applies high pressures (600 kb) on up to 6-ft^2 surfaces. Flying plate techniques also employed.	Determination of Hugoniot equations-of-state on: Coments Epoxies Geological material Concrete (Hardened specimens).	Time-dependent measurements of: Pressure Strain Time of arrival High-speed oscillographs and magnetic tape recording High-speed cameras.
Waterways Experiment Station Vicksburg, MS	Compressed-gas and powder gun facility.	Gas gun 20 ft x 2-in. dia. operated by high-pressure helium or nitrogen. Specimen launched into evacuated tube. Powder gun: 20 ft x 2.5-in. dia. Explosive driving of specimens up to 8000 ft/sec. Launch tube evacuated and detonation products contained.	Shock response or Hugoniot data on geological materials, grouts, and concretes.	Particle velocity time and pressure time. Oscillograph recording.
NCEL Port Hueneme, CA	Dynamic slab loader.	Primacord driver. Maximum pressure: 300 psi. Maximum force: 1,560,000 lb. Rise time: 1 to 3 ms. Decay (several sec).	Tests of reinforced concrete slabs.	Oscillograph recording. Oscilloscope photography.

Table B-4. Full-Scale Soil Loading Tests of Airblast Effect During Field Tests

TABLE B-4. FULL-SCALE SOIL LOADING TESTS OF AIRBLAST EFFECT DURING FIELD TESTS

FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS
HEST Air Force Weapons Laboratory Kirtland AFB, NM	Primacord laced around wooden racks and detonated in an air cavity benearth an earth overburden.	Ground surface air overpressures in excess of 1000 psi possible. Accommodates very large test structures.	Actual prototype, buried systems, models of systems, and soil/structure interaction.
DIHEST Air Force Weapons Laboratory Kirtland AFB, NM	Arrays of explosives embedded in the ground.	Horizontal longitudinal peak partical velocities of nearly 100 fps at a range of 10 ft possible. Accommodates full-size test structures.	Buried systems in a variety of geological formations. DIHEST coupled with HEST provides simulations of air-blast-induced and direct-induced ground motion.
DELTA Civil Engineering Research Facility Kirtland AFB, NM	Explosive cavity above or below test slab inside reinforced concrete cylinder.	30,000-psi maximum, 13-ft-dia. test section, 2-day assembly for each test.	Models of systems, test to failure.
DRES Portable Ralston, Alberta Canada	Horizontal layer of explosive with water overburden can be placed over any existing buried structure to be tested.	30 to 100 psi overpressure range. Positive duration, 40 ms. Ground surface cover is 17.5 x 16 ft.	Portable ground-blast simulator places time-dependent overpressure loads on existing buried targets.
Blast-Directing Techniques DRES Ralston, Alberta Canada, and AWRE Foulness, England	HE arranged in vertical flat plate.	Cost well below similar pressure resulting from hemispherical trials. 30 to 450 psi range. Target dimension should be smaller than the HE reactangle.	Test of full-scale equipment.

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Table B-5. Dynamic Water Wave and Shock Tests, Simulating Airblast o Direct Shock
Table B-6. Blow-Off Response Using Sheet Explosives to Simulate Nuclear Radiation Effect

TABLE B-5. DYNAMIC WATER WAVE AND SHOCK TESTS, SIMULATING AIRBLAST ON DIRECT SHOCK

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FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
WES Vicksburg, MS	Big black river test facility.	Basin 1: 150 ft x 250 ft x 22 ft deep. Detonations up to 150 lb HE. Basin 2: 160 ft x 260 ft x 12 ft deep. Detonation up to several hundred pound HE. Basin 3: Trapezoidal with sloping bottom 550 ft long; 300 ft wide at 0.2 ft depth, 150 ft wide at 12 ft depth.	Underwater explosion effects. Explosively generated surface effects.	Time-dependent measurements of: Pressure Surface Displacement Bottom Ground motion High-Speed cinephotographs up to thousands of frames/sec.
Lovelace DNA Kirtland AFB Albuquerque, NM	Water shock facility.	Basin 220 ft x 150 ft at top, 30 ft deep over a 30 ft x 100 ft portion. Upper limit of detonations 27 lb.	Biomedical investigations of underwater blast effects.	Time-dependent measurements of: Pressure Oscillograph Records.
NCEL Port Hueneme, CA	Impulse water wave facility.	Basin 94 ft x 92 ft x 3 ft deep. Compressed-air-driven plunger. Single abrupt and omnidirectional motions of the plunger are used.	Effects of water waves on model waterfront structures.	Cinephotography.

TABLE B-6. BLOW-OFF RESPONSE USING SHEET EXPLOSIVES TO SIMULATE NUCLEAR RADIATION EFFECT

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FACILITY	EQUIPMENT	PERFORMANCE	TYPE OF TESTS	TYPE AND FORM OF RESULTS
Any facility familiar with HE techniques	Explosive sheet in contact with specimen	10^4 taps - 0.2 ms (time proportional to impulse), 100 kb peak pressure. Maximum achievable is probably less than 10^7 taps - 10^7 taps gives a 200-ms pulse.	Radiation impulse loads of closures, exposed structural elements.	--
	Explosive sheet over neoprene foam	3000 taps on up, 2000-2 ms 0.1 to 10 kb	--	--
	Light-initiated explosives (lead or silver azide)	1/4 sec pulse	Under development-dangerous to work with	--
	Explosive mesh	5000 taps minimum 1 ms rise time and 2×10^{-8} simultaneity claimed	--	--

Table B-7. Tests of Nuclear Radiation Effects
Table B-8. Tests of Thermal Radiation Effects

TABLE B-7. TESTS OF NUCLEAR RADIATION EFFECTS

EFFECT TO BE SIMULATED	SIMULATION TECHNIQUE	ENVIRONMENT OR CHARACTERISTIC	COMMENTS--REMARKS	AGENCY TEST SITE
Penetration of Neutrons and Neutron-Induced Radiation	Plasma Focus Device (Zipper)	Total 10^9-10^{11} w/shot 14 mev n 1/2 sec duration	Can be repeated at about 1 min intervals. Needs development to be portable. Kaman Nuclear has best capability.	Kaman Nuclear
	Fissionable Plate + N Source	Fission spectrum probably largest flux		
	Pulsed Reactors	Fission spectrum up to 10^{13}n/cm^2 and up to 10^7 rad (c) 50-100 sec pulse	From 1963 survey Super Kuka Minimum of 10 sec irradiation	Battelle Memorial Institute
	Steady-State Reactors	Maximum of 6 x 10^{15}n/cm^2 sec	To match	
Penetration of Gamma Facilities	Underground Gamma Facilities	Maximum of 10^8 rad(c)/hr more common is 10^6 rad(c)/hr	Minimum of 1/2 hr, question of spectra must be resolved.	AEC, NTS
	Gamma Irradiation Facilities	500-Curie source irradiation 20 in. spec at 10^6 rads/hr 500-Curie source irradiation 20 in. spec at 1.3 x 10^5 rads/hr	Numerous facilities and places	Martin Co., Baltimore
Permanent Neutron Damage	Pulsed Reactors	10^{15}n/cm^2 (fission) 600 sec	Use internal chambers for irradiation--largest Super Kuka to be operated in 1968.	LRL, Super Kuka
Transient Radiation Effects Electronic System (TREES)	Prompt Gamma Simulator	Optimum specimen size Length: 50 cm Diameter: 50 cm Target Distance: 75 cm Pulse Length: 70 x 10^9 sec Max 5000-7000 rads/pulse 10 in. rads/sec	(Circa 1967)	USAF/AFSWL, Kirtland AFB

TABLE B-8. TESTS OF THERMAL RADIATION EFFECTS

EFFECT TO BE SIMULATED	SIMULATION TECHNIQUE	ENVIRONMENT OR CHARACTERISTIC	COMMENTS--REMARKS	AGENCY TEST SITE
Thermal Radiation on Exposed Elements	Rocket Engine Exhaust Chemical		Can verify subsystem calculations. Simulation not really representative in heat/time relations.	Rocket Test Stands
Thermal Radiation on Exposed Elements	Thermal Simulator	Thermal Jet 3-5 cal/cm^2/sec for 10-cm specimen.	Not fully developed; requires 3-5 year development program small samples; could provide repeatable tests.	DASA
Thermal Radiation on Exposed Elements	Nuclear Explosion Shock Tube (NEST)	Proposal-stage attempt to simulate effects of a surface nuclear burst including thermal radiation, 1/4 subscale model.	Thermal radiation is also produced in this concept. See detailed write-up on (Above appraisals circa 1967)	AEC/DASA, NTS

Table B-9. Tests of EMP Effects

TABLE B-9. TESTS OF EMP EFFECTS

EFFECT TO BE SIMULATED	SIMULATION TECHNIQUE	ENVIRONMENT OR CHARACTERISTIC	COMMENTS--REMARKS	AGENCY OR CONTRACTOR
EMP E-Field B-Field	Miniature Freme	Max E Field: 2.5×10^5 V/m Max B Field: 120 Gauss Rise Time: 0.1×10^{-6} sec Duration: 5×10^{-6} sec Spec Size: 5 ft dia. x 6 ft long	Small-scale component or subsystem testing	US Army, ERDL Ft. Belvoir, VA
EMP E-Field B-Field	Freme	Max E Field: 10^5 V/m Max B Field: 60 Gauss (uniform to 10%) Rise Time: 0.5×10^6 sec Max Spec Size: 50 ft dia. x 60 ft long	Full-scale samples of subsystem	US Army, ERDL Ft. Belvoir, VA
EMP E-Field	ALECS	Max E Field: 10^4 V/m Rise Time: $3\text{-}10 \times 10^{-9}$ sec Duration: 100×10^6 sec	Subsystem or scale samples	AFWL, Kirtland AFB
EMP E-Field	ALECS	Max E Field: 7.5×10^4 V/m Rise Time: $5\text{-}10 \times 10^{-9}$ sec Pulse Width: 150×10^{-9} sec	Subsystem or scale samples	AFWL/LASL
EMP E-Field	ARES (Advanced Research EMP Simulator)	Pulse Characteristics-- Peak Output Voltage: 45 MV Energy Storage: 50 kJ Field Strength in working Volume: 110 kV/m Pulse Rise Time: 6×10^{-9} sec Duration: $100\text{-}500 \times 10^{-9}$ sec	Facility has a working volume 40 m high, 30 m long, and 40 m wide. Shielded instrumentation room housed beneath the facility.	DNA, Kirtland AFB
EMP	Orange Bank Generator	Pulse Length characteristics-- Longest: 500-μsec rise 750-μsec decay Shortest: 6-μsec rise 100-μsec decay Variable frequency control Capacitor discharge 7 kV - 45 kV 20 kA maximum	Small portable unit Component Testing	AFSWC/SWTVE, Kirtland AFB
EMP E-Field	Marx Generator (Small)	Pulse Length Characteristics-- Longest: 500-μsec rise 750-μsec decay Shortest: 6-μsec rise 100-μsec decay Variable frequency control Gap discharge 1.4 mV - 15 mV 50 kA maximum E Field 10^3 - 10^4 V/m	Small portable unit for subsystems and components	AFSWC/SWTVE, Kirtland AFB Lightning Transient Research Institute
EMP E-Field	Marx Generator (Large)	Pulse Length Characteristics-- Longest: 500-sec rise 750-sec decay Shortest: 6-sec rise 100-sec decay Variable frequency control Ignition discharge 80 - 320 kV 160 kA maximum	Large portable unit can be taken to sites for full-scale testing.	AFSWC/SWTVE Kirtland AFB and Field Sites
EMP E-Field H-Field	Test Generator	H Field - 1 kHz damped since Wave Peaking at 100 Gauss E Free Field - 10 kV/m at 2 m	In-plant small samples	Boeing Co., Seattle, Washington

TABLE B-9. (CONTINUED)

EFFECT TO BE SIMULATED	SIMULATION TECHNIQUE	ENVIRONMENT OR CHARACTERISTIC	COMMENTS--REMARKS	AGENCY OR CONTRACTOR
EMP	SCREEN Rooms + Generators + Elect. Test Equipment	Variable, depending on location and contractor	In-plant testing, subsystems and scaled components to full-scale components.	Numerous
EMP	Synthetic Pulse Diagnosis (SPUD)	Measurement of CW transfer functions inside an enclosure when transmitted at the surface	Proposal by TRW full-scale tests at actual sites	TRW Systems, Actual Test Site
EMP E-Field	HEMP	Pulse Characteristics-- Max voltage: 400 kV Max field: 26 kV/m Rise time: 3×10^{-9} sec Decay time constant: 300×10^{-9} sec	No working volume section; just 2 transition sections each 68 m long. Junction of sections is 15 m high and 24 m wide.	SAFEGUARD Communication Agency, Fort Huachuca, AZ
EMP E-Field	SIEGE (Simulator-Induced EMP Ground Environment)		Working volume is 3m high and uses the earth as the lower plate. Multiple drives, using 8 Ω transition. Designed to test a buried system.	SAFEGUARD Communication Agency, Fort Huachuca, AZ
EMP E-Field	TEFS (Transportable Electromagnetic Field Simulator)	Pulse Characteristics-- Field strength: 50 kV/m Rise time: 4×10^{-9} sec Decay time constant: 350×10^{-9} sec	Propagate transient in the vertical downward direction. Multiple feeds (144) each driving 4 transition sections (576 total) Can illuminate a 40 m x 40 m area	SAFEGUARD Communication Agency, Portable, can be erected on site
EMP E-Field	Sandia Long Wire	Pulse Characteristics-- Rise time: 10×10^{-9} sec Duration (to 10%): 1×10^{-6} sec Peak field strength: $\approx$ 1000 V/m at a point 100 ft from wire.	Facility is 1000 ft long mounted on 40-ft poles. Powered by two 20 kV power supplies.	Sandia Corp., Kirtland AFB
EMP E-Field	Martin-Marietta Long Wire	Pulse Characteristics-- Rise time: variable $5 \text{ to } 30 \times 10^{-9}$ sec Pulse width: variable $100 \text{ to } 700 \times 10^{-9}$ sec Max field strength: 1100 V/m at 100 ft Pulse repetition frequency: 10 pps	Facility is 1000 ft long and 46 ft aboveground. Powered by two 125 kV power supplies.	Martin-Marietta Corp., Orlando, FL
EMP E-Field	AFSWC Dipole (Long Wire)	Pulse Characteristics-- Rise time: 7×10^{-9} sec Duration: 200×10^{-9} sec Field strength: 300 V/m at 90 m Repetition rate: 10 pps	Wire is 320 ft long and 45 ft aboveground. Located adjacent to an aircraft parking pad at Kirtland AFB.	AFSWC, Kirtland AFB
EMP E-Field	HDL Biconic	Pulse Characteristics-- Rise time: 4×10^{-9} sec Zero crossing at decay: 900×10^{-9} sec Field strength (at 90 m): 4.5 kV/m	Biconic sections 9 ft dia. x 9 ft long. Overall antenna length is 1000 ft mounted 100 ft aboveground.	Harry Diamond Labs Woodbridge, VA
EMP E-Field	RES		A flyable (helicopter) Biconic radiator. Horizontal version is 200 ft long, vertical version is 600 ft long. Design is similar to HDL simulator.	AFWL, Portable

TABLE B-9. (CONCLUDED)

EFFECT TO BE SIMULATED	SIMULATION TECHNIQUE	ENVIRONMENT OR CHARACTERISTIC	COMMENTS--REMARKS	AGENCY OR CONTRACTOR
EMP E-Field	NOL/ITTRI Hybrid Antenna	Uses a vertical conic antenna (50 ft high) and a horizontal fringing line (300 ft) Pulse Characteristics-- Rise time: 10×10^{-9} sec Decay time: $1\text{-}100 \times 10^{-6}$ sec Field strength: 100 V/m single shot, 10 V/m at 60 pps.	Sub-threat-level facility uniform fields developed in the 20 x 50 m interaction area.	NOL/ITTRI Crystal Lake, IL
EMP E-Field	Hybrid Antenna	Similar to NOL/ITTRI, above but larger and more powerful. Design criteria include: Length: 1300 ft (fringing line) Height: 100 ft (conic antenna) Field strength: 1000 V/m at 300 m	To be built at Solomons, Maryland for Navy use. (comment Circa 1973)	NOL, Solomons, MD
EMP E-Field	DELTA Function Simulator	Pulse Characteristics-- Vertically polarized Pulse width (at 50% points) 2×10^{-9} sec Field strength: 5 V/m at 5 ms Beam width: +20 deg.	Installed on a mountain top at White Sands Missile Range to evaluate aircraft in flight.	White Sand Missile Range, New Mexico
Debris Testing Components	CER Filter and Dust Separator Test	Critical component debris test	Used to verify design and calculations.	Contractor, In-Plant
Maximum Debris Load-- Debris Removal System	Operating Test Fixture	Operation of debris removal systems under maximum load.	Laboratory test to confirm design of debris removal system	Contractor, In-Plant
Debris Removal	Operational Test to Demonstrate Debris Removal System	Selected debris to simulate maximum load.	Full-scale operational prototype system may be conducted in conjunction with other closure testing.	Contractor plus OCE, Field

Table B-10. Chronology of HEST and DIHEST Tests

TABLE B-10. CHRONOLOGY OF HEST AND DIHEST TESTS

DATE	TEST	LOCATION	PURPOSE	PIT SIZE, FT
Feb to Aug 1964	Phase I (Gas Bag)	Kirtland AFB	Experiment with (1) gas mixture/water overburden and (2) detonating cord/sand overburden. Selected latter method.	20 x 40
Dec 1964	Phase II	Kirtland AFB	Determine pressure area and instrument requirements for a full-scale Minuteman facility, using a quarter-scale model.	96 x 150
Feb 1965	(HEST-2)	Kirtland AFB	Study parameters controlling the HEST air-pressure time histories.	32 x 36
Mar 1965	(HEST-3)	Kirtland AFB	Study parameters controlling the HEST air-pressure time histories.	40 x 48
May 1965	Phase IIA	Kirtland AFB	Double overpressure, change surcharge containment, and improve instruments, using same testbed and structures as for Phase II.	88 x 100
July 1965	Collins Antenna Test	Kirtland AFB	Using facility similar to Phase IIA, include a cavity for investigating response of LEB access and air entrainment systems and antenna.	40 x 96
1965	Parameter Studies	Kirtland AFB	Study parameters controlling the HEST air-pressure time histories.	Various
Oct 1965	(HEST-1)	Kirtland AFB	Study parameters controlling the HEST air-pressure time histories.	32 x 36
Dec 1965	HEST Test I (Quick HEST)	Warren AFB Wing V	OPERATIONAL TEST: Test an operational Minuteman site with launch facilities and a ground test missile on simulated alert.	302 x 304
Mar 1966	(HEST-6)	McCormack's Ranch, Albuquerque	Study free field ground motion.	
May 1966	HIP 1	Kirtland AFB	Improve HEST environment.	40 x 60
June 1966	HIP 1a	Kirtland AFB	Improve HEST environment.	40 x 60
July 1966	HEST Test II	Warren AFB Wing V	OPERATIONAL TEST: Demonstrate the degree of structural survivability of facilities and equipment; assess the hardness.	304 x 352
Sept 1966	HEST Test III	Grand Forks AFB	OPERATIONAL TEST: Substantiate the hardness of test site to meet design attack threat; obtain data for extrapolation of Minuteman force hardness; demonstrate missile launch capability after test.	302 x 304
Dec 1966	Drillhole	McCormack's Ranch, Albuquerque	Study free field ground motion.	64 x 148
July 1967	Backfill (HEST-4)	McCormack's Ranch, Albuquerque	Study free field ground motion.	56 x 72
Oct 1967	HEST V Demonstration	Grand Forks AFB Wing VI	Demonstrate maximum SOR environment; evaluate surcharge disposal; evaluate gage placement techniques; provide planning basis for HEST Test V. Used smaller pit.	64 x 83
Apr 1968	Mini-Can I	Kirtland AFB	Verify design for Prairie Flat overpressure facility for Project LN320; however, shock wave outran detona-front and broke detonating cord.	31 x 75
May 1968	Mini-Can II	Kirtland AFB	Using same site as for Mini-Can I, try 1/16-in. aircraft cable support for detonating cord, but also broken by shock wave.	31 x 75

TABLE B-10. (CONCLUDED)

DATE	TEST	LOCATION	PURPOSE	PIT SIZE, FT
May 1968	Mini-Can III	Kirtland AFB	Using same site as Mini-Can I and II, try two methods for protecting detonating cord; one was successful for protection, but failed to meet requirements for shock front velocity and impulse.	31 x 75
Sept 1968	HEST Test V	Grand Forks AFB Wing VI	OPERATIONAL TEST: Determine structural survivability and functional capability of launch-essential systems; obtain data useful for force hardness assessment.	300 x 300
Sept 1968	Prairie Flat HEST Test (Proj. LN320)	Suffield Range, Canada	HEST Test with model structure; obtain free field motion and structure response data at specific range and overpressure levels to compare with those produced by 500-ton Prairie Flat Trial.	104 x 108
Nov 1968	Rocktest I	Albuquerque	Research in nuclear weapons effects and systems development, as applicable to structures in hard rock.	160 x 208
1969	DATEX I	Cedar City	DIHEST Development: Provide information on direct-induced rock stresses for HANDEC I experiment.	
May 1969	HANDEC I	Cedar City	Demonstrate Improved simulation of a nuclear blast by combining a HEST with DIHEST input to ground motion.	40 x 60
Aug 1969	HANDEC II	Cedar City	Follow-on to HANDEC I, with reduced overpressure while DIHEST was increased nearly 20 times.	60 x 90
Oct 1969	DATEX II	Cedar City	DIHEST Development: First employment of a slurry explosive as a loading source.	185 x 200
Mar 1970	Rocktest II	Cedar City	Test realistic configurations of Minuteman launch structures to survive the HEST-DIHEST environment in rock, using ten experimental structures.	250 x 400

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e. In the testing community the validity of the equipment to produce simulated airblast-induced ground motions is much debated. The HEST loading is a moving pressure over a bed with finite width and length. The true nuclear-induced loading more correctly resembles a line load with a step pulse behind the front. The fact that the HEST is loading only a small area creates an outward and upward motion adjacent to the bed; the true nuclear is essentially a one-dimensional motion. This outward and upward motion in HEST may significantly alter the vertical component of motion near the center of the bed and consequently there may be a low validity for HEST to simulate airblast-induced ground motions.

f. BLEST (Berm Loaded Explosive Simulation Technique) is a technique to supplement the HEST method by using an array of shallow-buried charges in the area adjacent to HEST structure. initiated in proper sequence with the HEST Event, it generates an extended downward loaded area, minimizing, for a while, the undesired outward and upward motion in the vicinty of the HEST area itself. The design permits simulation detonations that allow the test structure to react fully to the primary stimulus before boundary effects distort the loading. A relatively new addition to the simulation techniques, it holds promise of reducing the size of the HEST structure itself while improving simulation. For further information on the theory and on test results, see Schrader et al. (1976) and test reports on the HARDPAN I test series that used the method.

Table B-11. Chronology of High-Explosive Tests

TABLE B-11. CHRONOLOGY OF HIGH-EXPLOSIVE TESTS

DATE	TEST	LOCATION	SIZE OF CHARGE; PURPOSE OF TEST
Feb 1964	Flat Top II	Nevada	20t TNT, spherical, half buried, desert playa, dry. To develop theoretical methods for predicting ground motion and cratering.
Mar 1964	Flat Top III	Nevada	20tTNT, spherical, half buried, desert playa, wet.
June 1964	Flat Top I	Nevada	20t TNT, spherical, half buried, limestone, dry.
July 1964	Snow Ball	Canada	500t TNT, spherical, surface. To simulate a 1kt surface nuclear burst.
1966-1967	Distant Plain:		
1966-1967	Event 1	Canada	20t TNT, spherical, on 85 ft tower.
1966-1967	Event 2a	Canada	Gas filled balloon, hemisphere on surface. Equivalent to 20t TNT.
1966-1967	Event 3	Canada	20t TNT, spherical, surface. To study close-in ground shock phenomena.
1966-1967	Event 4	Canada	50t TNT, Hemisphere, surface. To study blow-down effect in a forest.
1966-1967	Event 5	Canada	20t TNT, spherical, surface, frozen ground. To study cratering and ground shock in frozen ground.
1966-1967	Event 6	Canada	100t TNT, spherical, surface. To study scaling factors by comparing results for Events 6 and 1a, using identical instrument patterns.
1966-1967	Event 1a	Canada	20t TNT, spherical, center 29.5 ft above ground. To compare scaling factors with Event 6 above.
Aug 1968	Prairie Flat	Canada	500t TNT, spherical, surface. To further study scaling factors by comparison with Distant Plain Events 6 and 1a.
Oct 1968	Mine Under	Utah	100t TNT, spherical, 2 x charge radius above surface. To study cratering and shock effects over rock surface.
Nov 1968	Mine Ore	Utah	100t TNT, spherical, 0.9 x charge radius below surface. To study cratering and shock effects over rock surface.
Sept 1969	Mineral Lode	Utah	14t slurry, sealed cavity, 100 ft below surface. To study ground motion with fully contained detonation in rock.
Oct 1969	Mineral Rock	Utah	100t TNT, spherical, surface. Further study of ejecta and motions in rock surface.
Aug 1970	Dial Pack	Canada	500t TNT, spherical, surface. Further study of scaling factors, for comparison with Distant Plain Events 6 and 1a, and Prairie Flat, using same configuration over same geologic medium.
July 1972	Mixed Company	Colorado	500t TNT, spherical, surface. To simulate a 1.8 kt surface nuclear burst over a layered geologic medium.
Sept 1971	Middle Gust I	Colorado	20t TNT, spherical, half buried, clay over shale with water table 10 ft below surface. Middle Gust series to study effect of water near surface.
Dec 1971	Middle Gust II	Colorado	100t TNT, spherical, 2 x charge radius above surface, clay over shale with water table 10 ft below surface.
Apr 1972	Middle Gust Gust III	Colorado	100t TNT, spherical, surface, wet, clay over shale with water table 10 ft below surface.
June 1972	Middle Gust Gust IV	Colorado	100t TNT, spherical, surface, clay over shale with no near-surface water.
Aug 1972	Middle Gust Gust V	Colorado	20t TNT, spherical, half buried, clay over shale with no near-surface water.
Spring 1976	Pre-Dice Throw I & II	New Mexico	120t ANFO (100t TNT equivalent) Cylinder plus hemisphere, surface; desert alluvium ground-shock measurement and exposure of structures and equipment.
Oct. 1976	Dice Throw	New Mexico	600t ANFO (500t TNT equivalent) Cylinder plus hemisphere, surface; desert alluvium air-blast exposure of equipment and structures.

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B-3. Direct-induced high-explosive simulation technique (DIHEST).

a. The DIHEST development began in 1967 and uses a buried array of high explosives to produce a specified particle velocity history in the soil at a given range from the array. Because of time constraints, the developmental DIHEST study was restricted largely to simultaneous detonation of rectangular, planar, and vertical explosive arrays (table B-4).

b. In a buried retangular array of N sperical charges, one can argue that the peak horizontal particle velocity from the array can never be smaller than that obtained from one of the N sources (for sufficiently close source spacing). Furthermore, this lower bound should be approached as one moves closer and closer to the array. On the other hand, the peak particle velocity away from the explosive array should be a function only of the array geometry and total yield, and should be independent of the number of sources involved. In fact, it is expected that a reasonable upper bound (approached asymptotically with increasing range) is given by the peak particle velocity from a single spherical source of the total array yield.

c. A summary of particle velocity histories measured in the vertical symmetry plane at ranges of 30 and 60 ft from the DIHEST array suggests that:

—Horizontal particle velocity signatures were reasonably consistent within the lower two-thirds of the DIHEST depth.

—Horizontal particle velocity signatures were essentially the same form to be expected from contained spherical charges (in particular, no appreciable shear effects were observed).

—Horizontal peak displacements were consistent with those expected from a tamped, burried, spherical explosive of the same yield as the DIHEST array.

—Significant upward late-time motions associated with free surface effects would be produced by the DIHEST.

d. The DIHEST technique simulates, in a variety of geological formations, direct-induced ground motions expected from a nuclear device effecting buried strategic systems or a part of such systems. DIHEST coupled with HEST provides a capability of producing airblast as well as direct-induced ground motions on a variety of test items. Such testing is very expensive (\$2 $\times 10^6$), but may be a good value as the only viable technique under the ban on atmospheric nuclear testing. A chronology of DIHEST testing is included in table B-10.

B-4. High-explosive surface burst.

a. When nuclear experiments in the atmosphere were suspended in May 1963 by a presidential order preceding the nuclear test ban treaty, it was a crucial time for the suspension because a series of nuclear and high-explosive experiments were under way to compare ground motions from a nuclear surface burst with ground motions from a high-explosive surface burst.

b. Flat Top was a series of 20-ton HE experiments using blocks of TNT with the center of the spherical mass at the ground surface. Two experiments were conducted at an alluvium site and the third at a limestone rock site. In alluvium, the peak radial displacement measured near the surface was 24 in. at the 500 psi overpressure station. In limestone, the displacements were somewhat less (data were not reliable for the experiment in limestone).

c. Over the past decade, many HE field tests using built-up charges of high explosives have been conducted to satisfy the needs of specific programs. These tests often have been conducted in remote areas over land and water and in an arctic environment. Measurements included transient overpressure, ground shock and ground motion, water shock and water waves, as well as crater size and ejecta distribution.

d. Charge sizes up to 500 tons of TNT have been used. There are certain limitations involved with even these large-sized HE tests. For example, if the charge is detonated on or close to a soil surface, the crater formed interferes with the placement of buried or surface targets.

e. Two installations having permanent facilities to conduct large HE tests, 100 to 500 ton, are the Nevada Test Site (NTS) located near Las Vegas, Nevada, and operated by the U.S. Atomic Energy Commission; and the Defence Research Establishment, Suffield (DRES) located near Medicine e Hat, Alberta, Canada, and operated by the Defence Research Board of Canada. Large HE tests conducted at remote sites other than NTS and Suffield are expensive, and every effort is made to include in each test as many of the requirements as possible of the various defense and armed forces agencies.

f. HE tests to investigate various effects of airblast and ground shock are tabulated in table B-12. The tabulation begins with the Flat Top series and

TABLE B-12. GRABS TESTS: GIANT REUSABLE AIRBLAST SIMULATOR

DATE	TEST	TEST DESCRIPTION
July 1971 through 1973		GRABS tests have been conducted at Kirtland AFB, using a buried concrete cylinder 18 ft dia. x 30 ft deep, flush with the surface. Test objectives were to study structure/media interaction using a stiff structure of simple geometry within which well-defined soil media could be provided. The GRABS facility is a blast pressure chamber using a HEST-type environment.
	D-1	Development test: to test the facility and obtain soils data.
	D-2	Development test: to test the facility and obtain soils data.
	PI-1	Two models, stacked one on top of the other, in a dry sand medium.
	PI-3	Single model, 15 ft high, in dry sand medium.
	PI-4	Same model as PI-3, in wet sand medium
	PII-1	20-ft articulated structure, resting on floor of dry sand medium.
	PII-2	20-ft articulated structure, flush with surface, wet sand medium.
	PII-3	Upper half of PII-2 structure, resting on floor, dry sand medium.

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NOTE: This series of tests is expected to continue.

goes through the Middle Gust series.

B-5. Underground nuclear tamped burst.

a. Since the test ban treaty, two important underground nuclear experiments have been performed. HARDHAT and PILEDRIVER. These experiments were performed in the granitc rock in Nevada, at depths of about 1500 ft. A series of tunnel liners were located at varying ranges from ground zero (GZ), all in the high stress region, 0.5 kb to 4 kb. (Various liner concepts were used, such as liners with backpacking and rockbolting, and concrete liners poured directly against the rock.) A great deal has been learned about the cavity liner design for direct-induced motions.

b. The experiments have also demonstrated the capability to produce large ground motions expected from megaton surface bursts. From experiment to experiment, however, the data scat when scaled can differ by an order of magnitu testing a prototype facility for defined crite could be very difficult. This data scatter in t results may show the uncertainties in present-d design criteria.

c. Tamped nuclear experiments have been reco mend for testing Air Fence Launch Control Facil and Launch Facility structures, and may prod the best simulation of direct-induced motio Since calculations substantiate test results for pe stress, it is reasonable to expect that tests can designed to produce specified peak stress levels specified structure locations. The uncertainty in pected ground motion (primarily displacem must be considered in the design of the test.

B-6. Underground nuclear tunnel experiments.

a. Underground tests of nuclear weapon effects require the construction of a tunnel complex for installation of the weapon and the test specimens and apparatus, combining several experiments to get maximum use of the site. For moderate incremental program cost, structural testing experiments are added to events primarily designed for other experiments. The MIGHTY EPIC/DIABLO HAWK pair of events is such an instance.

b. The MIGHTY EPIC event at NTS was designed primarily to evalulate the radiation physics of a nuclear device using a line-of-sight (LOS) pipe. An LOS pipe is a conical tube aligned with its projected apex at the center of the nuclear device and extending radially outward for as much as a thousand feed or more. An LOS pipe is an expensive device to fabricate; in addition to requiring safety closures and test stations in various locations, it must also be capable of sustaining a hard vacuum on the inside (required to prevent attenuation of radiation along the interior of the pipe). MIGHTY EPIC is a landmark event to designers of hardened structures because of other programs that were conducted at the same time.

c. For the structures program, several types of cylindrical and spherical structures were tested. Three separate drifts were constructed at ground ranges from the nuclear device that would produce the design stress level, one-half design level, and twice design level. One of the novel features of this experiment was the placement of nine copies--as identical as could be constructed--of a spherical reinforced concrete structure. They were installed in sets of three at each stress level. It was expected that the close-in models would fail, the mid-range models would sustain moderate damage, and the distant units would be unscathed. In general, the actual test results followed theory, and the replication of test structures at each stress range gave a data base for evaluating the random variations of design parameters. Additional benefits will accrue from the DIABLO HAWK event (see e below).

d. Another objective of the MIGHTY EPIC event was to test theory that structures sited in a hard medium overlaid by an extensive layer of more porous medium would experience a more moderate environment than if they were sited at an equal depth in an all-hard medium. MIGHTY EPIC was sited in a quartzite bed overlaid with tuff. A useful amount of data was collected with which it is possible to evaluate the concept. The serious researcher is encouraged to seek out the data in the classified MIGHTY EPIC progress reports.

e. DIABLO HAWK, a follow-on to MIGHTY EPIC planned for the same test bed, is designed and will be located to provide a repeat loading of the structure tested in the MIGHTY EPIC event. This second loading of the structures will provide a stress wave propagating approximately 90 deg to the original MIGHTY EPIC stress wave direction. Such cyclic loading is rare in dynamic testing, outside of small-scale models in laboratories. Access to the structures was gained by retunneling into the test bed and opening the access ports. Extensive photographic coverage and dimensional mapping were performed after the MIGHTY EPIC event and have become "pretest measurements" for the DIABLO HAWK event, scheduled for some time in 1978.

B-7. Giant reusable airblast simulator (GRABS).

a. The GRABS is a cylindrical silo, 18-ft dia. by 48-ft deep and lined with reinforced concrete, constructed in a massive limestone formation at Kirtland AFB. New Mexico. It was developed to provide a two-dimensional zxisymmetric test facility for evaluating the computational predictions of the vertical motions of missile silos from overpressure.

b. A preselected amount of soil (up to 30 ft) is placed in the lower portion of the facility along with instrumentation and model structures, and a modified HEST is used to generate overpressure within the facility. This technique has the demonstrated ability to reproduce reasonably the air pressure history up to the ~1800 psi overpressure level from a 1-Mt surface burst. For a predetermined time, the technique confines within the facility a high-explosive detonation in a finite volume. This is done by using soil as a surcharge above an explosive cavity. The peak pressure, initial decay, and late-time decay can be controlled by variations in explosive charge density, initial explosive cavity volume, and the height and density of the surcharge material, respectively. The detonation projects the surcharge into the air, thereby eliminating the need for reaction devices. The surcharge support system is designed so that no braces extend to the test-bed; thus only the detonation shock is transmitted to the test-bed. Table B-12 is a list of tests conducted in the GRABS facility.

B-8. EMP simulation methods.

a. The EMP associated with a nuclear explosion can be considered an insidious effect, for it can do damage to unprotected systems at distances from the blast where other effects are not bothersome

(high-altitude bursts, for instance). However, its effects can be guarded against, and its consideration should be carried throughout the design and construction phase to achieve the best results for the least cost. Retrofitting EMP protective devices to a finished facility can be very expensive. Testing for design and hardness verification should be done at each significant step of the way. A summary of available facilities and techniques follows.

b. In the last decade, a large amount of research has gone into EMP and its cause, effects, and mitigation. Three documents of major significance to designers of hardened facilities summarize the state of the art quite well: GE-TEMPO, 1974 a; Schlegel, 1972; Bridge-Emberson, 1974. The following sections are extracted from the DNA EMP Handbook because it sets forth cogently the idea that attitude and prior analysis are so vital to the conduct of meaningful tests; less dedicated testing becomes mere busy work.

c. In general, EMP testing is expensive, time consuming, and filled with pitfalls that make it difficult to obtain credible results. Factors involved in deciding whether to engage in a test program and how to set it up include:

- — Priority of assessing vulnerability of the system under consideration
- —Simulation requirements based on system definition and postulated threat
- —Costs involved
- —Real-time requirements

Once the decision to test has been made, its success or failure depends, to a great degree, on the experience and attitude of the individuals directing it. A good test is one that:

- —Is viewed with a hypothesis at hand, derived by analysis;
- —Includes within its concept of accomplishment a statistical view of the problem;
- —Is conducted by experimenters who are constantly prepared to reject their hypothesis during the test, based on the evidence at hand, and who are willing to develop and investigate a new hypothesis if required.

d. A test should constantly be monitored by qualified analysts. For large-scale tests the analysts should be on-site as well as off-site to assess the progress of the test as it proceeds, redirect it if necessary, and see that the results are credible. The importance of analysis before the test cannot be overstressed, because it forms the necessary basis for continuous evaluation in terms of success or failure as the experiment proceeds. The required depth and extent of this analysis are matters of judgment, but even rough approximations are useful. Analysis is extremely difficult if it attempts to achieve high accuracy; even a transferfunction prediction for a real system can prove to be a challenging exercise. However, gross estimates must be made to determine feasibility in reasonble time and cost; these are based on generic groupings of the system and parametric analysis of these groupings. In this type of analysis, there is no substitute for experience; the experienced analyst has at his fingertips a storehouse of analytical tools, experimental data, and knowledge of what has and has not succeeded in the past. This perspective is a vital factor in achieving reasonably analytical results in a short time.

e. In EMP tests, nothing is precise. Neither the simulation, nor the instrumentation, nor the data reduction, nor the system behavior itself is absolute. All vary, and many introduce errors. It is essential that this be recognized early in the program. The fact that precision is impossible should not be interpreted as an excuse for carelessness. To the contrary, every reasonable effort should be made to minimize errors everywhere so that at the end of the program an assessment can be made that is as free from uncertainty as possible.

f. The problem must also be viewed statistically because the system under test may vary from unit to unit. Early recognition of this system variation will permit a more orderly pursuit of the end goal. If errors and system variability are not bounded the assessment of vulnerability can be totally in error. If errors and uncertainties are not minimized, the system may be penalized by excessive hardening requirements to cover not only the EMP effect but the large errors and uncertainties associated with the assessment of that effect.

g. It is important to think carefully at the beginning of test planning about what is desired as an output of the test and exactly how that result will be used in the assessment. Voltage and current waveforms might be collected (time domain) at low level with the idea of using linear extrapolations in time domain are invalid if the system is nonlinear. To cover this uncertainty, a high-level simulation using a reasonable pulse waveform is mandatory. At the same time, an analytical model of the system is highly desirable. Alternatively, transfer functions from external fields to voltages (for currents) in critical locations might be obtained (frequency-domain) with the idea of using these in analytical predictions. However, accurate transfer function determnation may require a simulation experiment different from that used in voltage or current determinations, and again the validity of a

transfer function depends on system linearity. Thus, obtaining both representative timedomain responses and system transfer functions with one simulation may not be compatible goals, and it is important to know what is needed and to have an alternative if the system proves to be nonlinear.

h. If the system behavior is truly nonlinear at the higher levels, then probably the only way to predict this behavior is by developing an analytical system model, including models of the characteristics of the important nonlinear devices or system segments. From this model, valid time-domain predictions can be made on a computer.

i. In general, the problem of assessing a system's vulnerability to EMP is not unlike a massive trouble-shooting problem in which the system may have several faults that must be located and corrected. The process is inherently an iterative one in which the experimenter learns, little by little, what the causes and effects are in the system and how detrimental effects can be prevented. Results toward this end will be achieved sooner if the data are collected carefully right from the beginning, since poor data can lead to erroneous conclusions, confusion, and delays.

j. The two approaches that can be used in attempting to establish criteria for what should be measured are to:

Work directly on circuits believed to be most critical and measure the input voltages of these circuits (a hazardous approach)

Work into the system from the outside, measuring first what the EMP induces on the exterior of the system, then systematically tracing the current flow from there to cabies, and along these cables to subsystem black boxes

k. The direct circuit approach is plagued by many traps. Voltage at the input of a particular circuit ignores the fact that the EMP may be coming in on a different circuit-interface wire such as ground or power or some other lead. To evaluate the "input" of EMP to that circuit, it would be necessary to measure the current or voltage on every wire leading to it. This may so load down the circuit (probes have capacitances that may not be negligible in their effects at these frequencies) that the data are useless. Connecting several probes into a circuit without bringing in some EMP currents is also a difficult matter. One of the greatest weaknesses of this approach, however, is that it may provide the semblance of data assessment without any real understanding of why the signal is at the circuit, why it looks as it does, and how it can best be eliminated. This type of premature assessment of systems is hazardous.

l. When a system is worked into from the outside, an overall understanding of system behavior is obtained sooner. At the same time, enough data can be obtained at subsystem or black-box interfaces to permit more detailed investigations to begin in the laboratory. Though there are some exceptions, this procedure is usually best.

m. What should be instrumented are those things that will answer these key points:

- How much current is induced on the exterior of the system.
- How much of this external current gets inside the system.
- How this energy gets inside.
- Where this energy goes and how it is distributed.
- What this energy does to each subsystem.
- How any detrimental effects can be eliminated.

n. These questions should guide the selection of points to be measured. Having selected all of the desired measurement points, it is probable that there will be too many to instrument at one time because of internal space limitations or other considerations. In this case, the measurements are best performed a few at a time, because instrumentation does load the system and change current amplitudes and distributions to a certain extent, and thus should be kept to a minimum.

o. Electromagnetic scale modeling is an important alternative to full-scale testing under the following conditions:

- Test facilities or available equipment are at a premium.
- The system to be tested is very large.
- The system dedication cost for full-scale testing is high. In

addition to the advantages of modeling under these conditions, benefits can be derived as follows:

- —Sensors can perhaps be better placed during full-scale testing as a result of model experiments.
- —Design modifications or cable reroutes can be made prior to fullscale testing.
- —Electromagnetic angles-of-arrival can be determined for worst- and best-case conditions.
- —Effects of change in the conductivity of surrounding media can be explored to an extent not possible in full scale.
- —Estimates can be made of some of the responses of a complex system prior to full-

scale testing.
—Quantitative data can be obtained to validate analysis.

p. It should be pointed out that because of the difficulty in introducing minute openings or poor bonds into models, and since these often control inferior fields, the usefulness of modeling is ordinarily limited to the measurement of limited value, and are generally appropriate only in confirming previous analysis. However, once the exterior fields, voltages, and currents are known for a complex structure, perhaps having cable runs, analysis can often yield internal field quantities of interest.

q. In actually setting up a scale model test, the following should be kept in mind.

(1) Broadband pulse response determination involves much more than does a steady-state, single-frequency response test.

(2) Special electromagnetic illumination sources are required that are coherent, have uniform time delay, and use antennas with constant effectiv height.

(3) Special modeling techniques are required for studying exposed conductors passing over or within a lossy dielectric, such as earth. A pulse-type waveform can theoretically be replaced by a continuous wave (CW) source with a sensing system that references the sensed CW signal to a reference phase from the source. Complex Fourier transfer functions can be developed by computer processing the recorded data. However, long sweep times are required to ensure that all narrow band responses are adequately explored, and the actual physical implementation of such an approach in the microwave band poses additional difficulties. On the other hand, the use of scaled real-time waveforms allows quick development of actual responses, from which complex Fourier transfer functions can also be developed with the aid of computers.

r. Scaling relationships are derived from the theory of electrodynamic similitude. We define the modeling factor, M, by:

$$M=\frac{D_a}{D_s},$$

where
D_a = A dimension of the actual system to be modeled
D_s=The same dimension of the scaled system

For example, when a 300-ft long structure is scaled down to a 30-ft long model, this 1/10 scale model has a modeling factor M 10.

s. The relations between scaled and actual quantities are:

Model Size	$D_s = d_a/M$	(B-2)
Frequency	$\omega_s = M\omega_a$	(B-3)
Conductivity	$\sigma_s = M\sigma_a$	(B-4)
Dielectric Constant	$\epsilon_s = \epsilon_a$	(B-5)
Permeability	$\mu_s = \mu_a$	(B-6)

t. A plane wave propagating in the positive z direction in an imperfect dielectric can be characterized by $H(z,t)=H_m e^{-zej(wt-z)}$ (B-7)

where H_m is the wave amplitude at z 0, a describes the wave attenuation in the dielectric, and B is the phase constant. a and B are real and given by:

$$\alpha = \omega\left[\mu\epsilon/2\left(\sqrt{1+\sigma^2/\omega^2t^2}\ -1\right)\right]^{1/2} \quad \text{(B-8)}$$

$$\beta = \omega\left[\mu\epsilon/2\left(\sqrt{1+\sigma^2/\omega^2t^2}\ +1\right)\right]^{1/2} \quad \text{(B-9)}$$

The wavelength, λ, in the dielectric is given by

$$\lambda=2\pi/\beta \quad \text{(B-10)}$$

and from equations B-8 through B-10, it is seen that α, β, and λ scale as follows:

$$\alpha_s=M\alpha_a \quad \text{(B-11)}$$

$$\beta_s=M\beta_a \quad \text{(B-12)}$$

$$\lambda_s=\lambda_a/M \quad \text{(B-13)}$$

u. A summary of EMP simulation test facilities is shown in table B-9. The listing is not all-inclusive by any means but does give an indication of the types of fixed facilities (relative) that are available. In the extensive literature available, methods are discussed for establishing test arrays at the facility to te tested.

v. Note that in the tables the simulator type includes stationary or fixed simulators, and portable ones. The only simulator listed that can be moved about and is not fixed is RES-I, which is helicopter-transportable. Pulse variability figures represent uncertainties in amplitude and decay times, and jitter represents the uncertainty in the firing time. Cycle time is the time between pulses.

B-9. Blast simulation techniques for testing air-entrainment systems and blast closures.

a. Comments are limited to methods available for testing overpressure on the performance of hardened air entrainment systems and blast closures under conditions simulating a nuclear attack. Tests specifically intended for the assessment of debris effects do not presently exist; therefore, comments in this area are directed to desirable tests and possible test techniques.

b. Shock-tube, implosion driver, and underground field tests have been instrumented to test overpressure effects on blast valves and air-entrainment systems (tables B-1 through B-4). The blast simulator at the WES is capable of producing environments with an upper pressure limit of 1000 psi; the physical size of the test chamber requires subscale models. The current pressure rise time is much too low for meaningful air-entrainment system tests, and it is not considered a useful facility for testing present or future air-entrainment systems.

c. Surface debris entering air-entrainment systems during a nuclear attack will come from four sources:

- Particulate material entrained in the air shock flow
- Surface material from cratering moved past the entrance
- Crater ejecta descending from aerial trajectories
- Particulate fallout from the nuclear cloud

d. Surface debris from overpressure flow will be relatively small particles carried into the air entrainment systems by the flow velocity behind the air shock. This material will be distributed throughout the air entrainment system, although very little material should reach the vicinity of the blast valve. Test simulation of this debris will be very difficult because a method of entraining the proper particle size and velocity distributions is not available. Some of this debris will be removed from the facility during the negative overpressure phase, and it is not expected that the residue will constitute a threat to the facility. Future improvements in the analysis of two-phase shock flows may lead to tests that might accurately assess the distribution of this material in air entrainment systems (table B-10).

e. Cratering causes most of the debris impinging on facilities. For sufficiently large weapons and close detonations, the air-entrainment system surface entrance may be engulfed in debris material from cratering. A substantial amount of this debris may collect in the debris pit of the air entrainment systems, but very little should enter the blast-valve trigger or delay lines.

f. Simulation of this debris flow is complicated by lack of test data from nuclear blasts, and lack of adequate scaling principles from HE to nuclear blast. Tests of some value could be performed by using large chemical explosives in close proximity to full or scale models of air-entrainment systems. Similarity of test site media to that of proposed facility locations would be important, since scaling of explosive effects between various types of soils is not well understood. Tests of this type would be of use in determining the likely distribution of various sizes of debris particles, the nature of blockages of the surface entrances, and methods of eliminating such blockages. To reduce the expense of these tests, combine them with other large HE programs, such as those conducted at DRES, Alberta.

g. Debris from the nuclear cloud will settle into the facility for some time after an attack, but will be concentrated primarily in the debris pit. Fallout distribution was studied in some detail at the time of surface nuclear tests, and can now be predicted with some assurance. A test that might be applicable for assessing the distribution of fallout material in an air-entrainment system could be performed by allowing equivalent size particles to settle into the entrance while the ventilation system was operating at a level appropriate to postattack conditions.

h. The distribution and importance of initial attack debris could be significantly altered by subsequent blasts. If multiple attacks are part of the design threat, place debris equivalent to that from an initial attack in an air entrainment system prior to performing a blast simulation

APPENDIX C
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GLOSSARY

Acceptance Region: The range of a statistic (in this text, the t-statist ic) for which the hypothesis is accepted as true.

Air-Entrainment System: Accomplishes a continous or periodic transfer of air (gas) between the atmosphere and the facility.

Bias Errors: Systematic errors resulting from imcomplete or inaccurate modeling, measurement errors, etc.

Binomial Distribution: A distribution where the values r/n for r 0, 1, ..., N have the frequencies

$$\frac{n!}{r!(n-r)!}\, p^r(1-p)^{n-r}$$

where p is the probabilty occurrence.

Blast Attenuator: A device for reducing in an air entrainment or exhaust duct. Wall friction, flow restriction, and expansion chambers are often used

Blast Valve: A valve that prevents entry of overpressure into hardened facilities.

Burst Conditions: A description of the location of point of burst relative to the ground surface and to the target.

Chi Square (χ^2) Goodness-of-Fit Test: A means of measuring the discrepancy between the Probability Density Function (PDF) exhibited by a data set and that for Gaussian, i.e., normal, or other hypothetical distribution.

Confidence Coefficient: The confidence level associated with the confidence interval.

Confidence Interval: The range within which an estimate will fall for a specified level of confidence, e.g., 90% of the time the difference between the mean of a normal population and the mean of an n-number sample will fall between $\pm 1.96\,\sigma/\sqrt{n}$.

Continuous Wave: A steady state excitation signal, e.g., cos ωt, as opposed to a transient or impulsive excitation. Frequency sweep or frequency stepping may be used to cover the broad frequency range of interest.

Correlation Coefficient: The ratio of the covariance of two random variables to the square root of the product of their variances, i.e.,

$$\frac{\sigma_{xy}}{\sqrt{\sigma_x^2\,\sigma_y^2}} = \frac{E\left[(x-\mu_x)(y-\mu_y)\right]}{\sqrt{E\left[(x-\mu_x)^2\right]\,E\left[(y-\mu^2_y)\right]}}$$

Delay Line: That portion of an air-entrainment system between a sensor and blast valve that allows valve closure before overpressure arrival.

Deterministic: having an assigned value; without uncertainty.

DIHEST: Direct-Induced High-Explosive Simulation Technique. A method using a buried array of high-explosives to produce a specified particle velocity time-history in the soil a given distance from the array. Coupled with HEST it can produce air blast and direct-induced ground motions on various targets.

Direct Injection: Excitation of a system or system element by direct application of electromagnetic signal, force, or displacement rather than by the application of such loads that pass through and are modified by intermediate elements such as protective structures and shock-isolation system or shielding.

DRES: Defense Research Establishment, Suffield. A semi-remote research facility near Medicine Hat, Alberta, Canada, where experiments requiring extensive land area can be conducted. Site of previous 100 ton and 500 ton high explosive tests.

EMP: Electromagnetic Pulse. Associated primarily with the high intensity radiation and conduction fields induced by nuclear explosions. Can produce extremely high currents in conducting element, disrupting or distroying electronic components.

Expansion Chamber: A type of blast attenuator for air entrainment/ exhaust systems which relies on the pressure-averaging effect of chamber fill time to mask or attenuate the maximum overpressure associated with sharp peaks

Failure Modes: Identifiable mechanisms of system or system element failureks e. g., communication system failure modes may include blast damage to antenna, EMP Burnout of antenna lead, ground-shock damage to antenna lead, EMP burnout of transmitter, shock and vibration damage to transmitter, power outage, etc.

Failure-Oriented Analysis: An analysis that examines occurrence/ nonoccurrence of failures capable of preventing mission function.

Fault Trees: A graphical presentation of the relationship between loads and failure modes and of their relation to system composition from the element through overall system levels.

Functional Block Diagram: A pictorial presentation of the operating relationship between system elements.

GRABS: Giant Reusable Air-Blast Simulator. A large Cylindrical silo in massive limestone at Kirtland Air Force Base, New Mexico. Designed to provide a 2-dimensional axisymmetrical test bed for air blast overpressure stimulus.

HARDHAT: A code name for an underground tamped nuclear event to evaluate hardened structural designs.

Hardness Compliance: Satisfaction of hardness requirement.

Hardness Verification: The process of determining that a system or system element has at least the resistance (hardness) claimed for it.

HEST: High-Explosive Simulation Technique. A method for simulating nuclear air-blast-induced ground motion.

Hydraulic Surge: Water hammer.

Ignorance Factor: A measure of that portion of the uncertainty resulting from incomplete knowledge of the phenomena or from bias or systematic error in measuring the phenomena, the uncertainty not related to the truly random natur of the phenomena.

Impendance: Mechanical impendance, the ratio of the acceleration of a mechanical system to a sinusoidal force exciting it.

$$Z(\omega)=\frac{\dot{X}(\omega)}{F(\omega)}$$

Intake Structure: That portion of an air-entrainment system where air enters the system.

Level of Significance: α, the chance of rejecting a true hypothesis; the complement of the level of confidence.

Lognormal Distribution: A statistical distribution in which the logarithm x of the variable y is normally distributed; its probability density functions:

$$\phi(y)=\frac{1}{y\,\ell_{ny}\sqrt{2\pi}}\exp\left[\frac{1}{2}\left(\frac{\ell n\, y-\ell n\, my}{\sigma_{\ell_{ny}}}\right)^2\right]$$

where $\sigma_{\ell n\, y}$ is the standard deviation of n y and my is the median value of y.

Low-Level Transient: Excitation by a transient signal simulating the threat time history but at amplitudes below those specified for the threat level.

Minimum Sample Size: The smallest sample from which a valid statistical inference can be made.

Mission Critical Functions: Those functions that are necessary to the execution of a system primary mission.

Monte Carlo Method: A technique that obtains probabilistic approximations to problems by executing a large number of simulation problems with parameters defined by statistical sampling.

Mounts and Fasteners: The mechanical components used to connect equipment to protective structures, platforms, racks, shock-isolation systems, etc.

Network Logic Diagrams: A graphical means of presenting the functional relationships of system elements, loads, and failure modes; similar to flow diagrams used in computer programming.

Nonparametric: Used here to denote those situations where either (1) the distribution is not a member of a known class (normal, lognormal, binomial, etc.) or (2) there are not enough data to allow identification of the distribution. Under these conditions estimates of parameters such as the mean and variance cannot be obtained. However, confidence intervals for quantities can be obtained.

Normal Distribution: Distributed in a Gaussian manner; i.e., having the probability density function

$$\phi(x)=\frac{1}{\sqrt{2\pi\sigma^2}}\quad \exp\,-(x-\mu)^2/(2\sigma^2)$$

where μ =mean and σ^2 =variance.

NTS: Nevada Test Site, under the control of DOE.

One-Sided Procedure: A statistical test wherin the hypothesis will be accepted if the statistic satisfies a one-sided condition of the form t x.

Overburden: Overlying soil or rock. .

Penetration: An opening that pierces the protective shell of a hardened . facility, such a a conduit for communication or power cables.

PILEDRIVER: Code name for an underground tamped nuclear event to evaluate concepts of hardened structure design.

Population: The set of objects or measurable effects having some common observable properties; for example, all Minuteman Launch facilities, or all thermo-nuclear explosions.

Probabilistic Assessment: methodology for addressing the influence of uncertainties in loads and resistances when assessing the hardness and survivability/vulnerability of hardened facilities.

Probability Density Function: A mathematical statement of the frequency of occurrence of possible values of a random variable (see, for example, Normal Distribution).

Probability Distribution: A function that assigns to each possible value of a random variable the probability of its occurrence. For continuous rando variables, the integral of the probability density function, also known as the cummulative distribution function.

Probability of Success: In this text, probability that a resistance exceeds its corresponding load, i.e., the probability that failure will not occur.

Protective Facilities: Facilities whose function is to protect material, equipment, personnel, and mission capability from the harmful effects of nuclear weapons.

Pulse-Train Simulation Test: A test in which system response is excited by a train of pulses designed to simulate the threat driving forces.

Radiation Shielding: Material that prevents penetration or reradiation of nuclear radiation environments—α, β, and γ-radiations from nuclear weapons.

Random Errors: Errors distributed according to chance, as opposed to bias or systematic errors.

Random Uncertainties: Uncertainties in the value of an attribute resulting from its random nature.

Repetitive Pulse: Excitation by a pulse train which covers the frequency range of the threat environment but may not simulate the time history of the threat pulse.

Resistance: Ability to withstand nuclear weapon-effect loads.

Resistance Design Goal: The level of resistance to be achieved to satisfy survivability requirements. Often stated in terms of local free-field nuclear weapon-effect environment amplitudes.

Shock-Isolation System: A system—mechanical, hydraulic, pneumatic, or hybrid—that attenuates the shock and vibration environment transmitted throug its elements.

Stationary Field: An EMP simulation for small components not sensitive to the transient nature of threat EMP pulses.

Survivability: The probability that a facility/Subsystem/component failure-mode will functionally survive a nuclear-weapon attack and retain its physical integrity during the specified endurance period.

Survival Probability: The probability that system or system element resistances exceed their corresponding loads.

System: A combination of elements, subsystems, or pieces of equipment integrated to perform a specific function.

System Engineering: A science dealing with the design and performance of interconnected components, subsystems, and systems.

System Hardness Level: The maximum load level for which a system retains functional capability at a prescribed level of confidence.

Systematic Error: An error resulting from bias in measurement, and not from chance. In this text, ignorance or imcompleteness of knowledge is treated as a systematic (nonrandom) error.

Systematic Uncertainties: Uncertainties due to unknown systematic errors or ignorance (incomplete knowledge).

Tap: 1 tap = 1 dyne-sec/cm^2

1 ubar-sec

14 $\times 10^{-6}$ psi-sec

Thermal Shielding: Material that provides protection from the thermal environment—radiation and fireball immersion—of nuclear weapon explosions.

TTCP: Tripartite Technical Cooperation Programme. Member nations are Canada, the United Kingdom, and the United States. s.

Threat Scenario: A description of the expected nuclear attack, including number of weapons, their yields, burst conditions, and timing of their detonation.

Transfer Function: A function relating free-field nuclear weapon-effect environments to local loads on a system or system element.

t Statistic: A statistic for comparing the sample and population means when the standard deviation is unknown.

Two-Sided Procedure: A statistical test wherein the hypothesis is accepted if the statistic falls between limits, i.e., $t_1 < t < t_2$, in contrast to a one-sided procedure where the statistic must satisfy an inequality of the form $t < t_1$ (or $t \geq t_2$).

Type I Error: Statistical probability of rejecting a hypothesis when it is true, i.e., an a error.

Type II Error: Acceptance of a hypothesis as true on statistical grounds when it is false, i.e., a B error.

Uncertainty: The amount (estimated) by which the predicted value may vary from the observed or true value.

Variance: The square of the standard deviation; for a finite sample the variance (S^2) is defined by

$$S^2 = \sum_{i=n}^{N} \frac{(x_i - \bar{x})^2}{N-1}$$

Weapon Range: The horizontal distance from the burst point to the target point, also called the "offset." The distance between burst point and target point is the slant range.

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